Analysis of Business Models for the Use of Additive Manufacturing for Maintenance and Sustainment

by

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Submitted in Partial Fulfillment of the Requirements
for the Degree of
Master of Science in Engineering
in the
Industrial and Systems Engineering Program

YOUNGSTOWN STATE UNIVERSITY

May, 2017

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Abstract

Aircraft operators must maintain and sustain their aircraft through the platform's life cycle. The Department of Defense (DoD) is no exception. Many DoD missions may require a time-sensitive production of spare parts. This lends itself to spare parts production by the Department of Defense itself and such an approach could be enabled by additive manufacturing. In order for the government to be able to produce spare parts in-house an entirely new business model between the original equipment manufacturer (OEM) and the government has to be established. A physical spare part would not be the transacted item; instead the technical data package (TDP) would be exchanged. Industry needs to be incentivized to adopt a data focused business model. A key question is can industry achieve equivalent profit similarly to the traditional spare parts production? This research explores business models from the perspective of industry. A survey was provided to both government and industry to identify differences and similarities in assumptions and expectations. Four different business models were developed. The business models were applied to two different case studies to evaluate the pros and cons of the various models.

This analysis provides industry and government a reference for discussions on approaches toward future maintenance and sustainment manufacturing operations.

Acknowledgements

I first want to express my gratitude toward my advisor, Dr. Brett Conner, associate professor of Mechanical and Industrial Engineering. Your mentorship and guidance started when I was an undergraduate at Youngstown State University. My research experience included research trips, conferences, networking and so much more that has shaped me as an individual. My passion for additive manufacturing would not be the same without all of the opportunities and motivation you provided me.

I would like to thank my thesis committee members Dr. Martin Cala and Dr. Darrell Wallace. Thank you for your time, feedback and guidance on the completion of my thesis.

Funding for this thesis was provided by the Air Force Research Laboratory through America Makes under cooperative agreement number FA8650-12-2-7230. The project is titled The Maturation of Additive Manufacturing for Low-Cost Sustainment and is led by the University of Dayton Research Institute. Thank you to America Makes for providing the research opportunity. Thank you to Deloitte Consulting for the discussions on business models.

I would like to thank the America Makes Maintenance and Sustainment Advisory group and the Department of Defense Additive Manufacturing Maintenance Operations group for the participation in the AM business model survey.

I would also like to thank Danielle Strong for riding this Industrial and System Engineering train with me for the past six years. Thank you for sharing this experience with me and also providing me the shipping costs for my thesis. We did it!!!

Lastly I would like to give a special thank you to my family and amazing fiancé, Matt. Thank you for always being here for me and supporting me through my college career. Your love and encouragement is greatly appreciated and without you I would not be where I am today. I love you Mom, Dad, Paul, Elizabeth, Sara and Matt!!

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Chapter 1 Introduction

Additive manufacturing (AM) also known as 3D printing is an evolutionary layer by layer manufacturing process developed in the 1980s but in the recent years is gaining attention. The aerospace, medical, and automotive industries were early adopters of AM [1].

1.1 Motivation

In May 2016 America Makes, formerly the National Additive Manufacturing Innovation Institute, along with Deloitte Consulting and Lockheed Martin hosted an additive manufacturing business model wargame [2]. A wargame, also known as a military simulation are analytic games which simulate warfare at the tactical, operational, or strategic level [3]. Ron Sanders, vice president of the consulting firm Booz Allen Hamilton explains, “By simulating real-world scenarios, the exercises enable key players to work through a wide range of problems and explore possible solutions without the threat of real-world consequences” [4]. For the AM business model wargame members of the government and industry came together for a couple days in order to work through the business transactions needed when a need exists for the Department of Defense (DoD) to produce parts additively manufactured in house and on demand in support of mission readiness [2]. The simulation guided participants through moves representing steps in the acquisition process. Four key areas of focus were identified: the AM ecosystem, security, liability & quality, and cost & profitability. The first AM business wargame allowed industry and government to identify business model issues. A second AM business wargame is scheduled for May 2017 and will be focused on how to take action and addressing the needs of both government and industry. After attending the first AM business model wargame, a realization of the need to conduct research on the topic was established and was determined as the focus for this thesis.

1.2 Research Questions

The goal of this research is to develop and identify business models industry can implement when there is a need from government to produce spare parts in-house. In order to address the research needs from the AM business model wargame several research questions were developed.

- If a manufacturer planned on producing spare parts and now the government wants to produce parts itself using AM, what revenue generation models for AM part data will allow a manufacturer to recoup revenue and profit losses?
- Of the business models in the analysis, how does variability in demand effect return on investment (ROI) and long term profits?
- Does the manufacturing process (traditional vs additive) industry uses to produce spare parts have an effect on the total profit and years needed to recoup non-recurring costs?
- What is the ideal profit margin industry should implement in order to recoup non-recurring costs within two years?
- If the government is going to produce spare parts in house using AM, what optimal stocking level and costs associated with inventory, and how do they compare to a traditional manufacturing process?

Chapter 2 Literature Review

AM for maintenance and sustainment is gaining attention from the aerospace and defense industries. As of 2011, the aerospace industry consisted of 12 percent of total AM production in the US, representing 0.02 percent of all aerospace manufacturing [5],[6]. In the Air Force, the three Air Logistics Complexes, Oklahoma City, Warner-Robins, and Ogden, are integrating AM into aircraft maintenance and sustainment efforts [7]. US Navy research on AM implementation concludes $1.49 billion would be saved annually on staffing and organizational cost alone with the application of AM into the maintenance programs [5]. Companies such as Boeing, Lockheed Martin, General Electric, Airbus, and others are interested in the reduced lead times, component weight, operational costs, environmental impacts and other aspects AM offers to lead to a significant impact on aerospace components [8]. More and more aerospace companies are realizing the benefits of AM, GE, in 2016, acquired 75 percent stake in Concept Laser, a German 3D printing company, and 76.15 percent of Arcam AB, a Swedish 3D printing company [9]. GE has invested $1.5 billion in AM and plans to continue to invest significant funds into the advancement of 3D printing technology [9].

Aerospace components can be constructed from advanced materials and contain complex geometries which leads to high costs and lead times using traditional manufacturing [10]. Producing products with AM, whether complex or simple are still produced layer by layer, in the same way, therefore complexity adds no extra costs or time [11]. Furthermore, aerospace parts are usually produced in small quantities, a maximum of several thousand parts. [10]. In conventional manufacturing tooling and other capital investments are expensive, therefore, parts are mass produced to recur the initial costs.

Low volume is ideal for AM, making aerospace applications highly suitable for the technology [10].

2.1 Additive Manufacturing processes

The additive manufacturing processes categories were defined by the ISO/ASTM Joint Group on Terminology by the ISO/ASTM 52900 standard [12]. The approved seven process categories are: material extrusion, material jetting, directed energy deposition, powder bed fusion, binder jet printing, sheet lamination and vat photopolymerization.

2.1.1 Vat Photopolymerization

Vat photopolymerization also known as stereolithography was the first process of the additive manufacturing era. Vat photopolymerization was introduced into production in 1988 and patented by 3D Systems' founder Charles W. Hull [13]. Vat photopolymerization uses a vat of liquid photopolymer resin and an ultraviolet light, used to cure the resin layer by layer. The liquid does not give a structural support therefore supports are needed [14]. Vat photopolymerization produces parts with high resolution, fine features, and smooth surface finishes [15]. The process is suitable for prototype parts and also for investment cast wax patterns. Vat photopolymerization is used for low volume production of wax patterns for investment cast aerospace engine components [16]. Photopolymer materials typically have low heat resistance and tensile strength, therefore, the process is commonly not selected to produce end usable parts. A new version of vat photopolymerization developed by Carbon is called Continuous Liquid Interface Production (CLIP) and promises 25 to 100 times faster printing speeds compared to standard vat photopolymerization [15]. With more functional and durable material chemistries, CLIP holds promise to open the door for the use of vat photopolymerization for production parts.

2.1.2 Material Extrusion

Material extrusion is a common 3D printing process where the material is extruded through the nozzle of the printer heated up and then deposited layer by layer [14]. Material extrusion printers range from industrial size to domestic and hobby size 3D printers. Material extrusion is ideal for prototyping and allows for quick and inexpensive design iterations. Supports can be melted away which allow for the production of lightweight and complex aircraft parts. The Gas Turbine Research Establishment (GTRE) of Bangalore, India experimented with material extrusion to create a fit and form non-functional prototype of a 2,500 component jet engine in six weeks. Traditional manufacturing would have taken a least a year and over $60,000, but with material extrusion and the material ABS, which is a high strength durable plastic, GTRE was able to save $40,000 and create a lightweight engine by combining several parts and using the water based solution to dissolve interior supports [17].

2.1.3 Binder Jetting

Binder jetting resembles the 2D printing with paper and ink jet heads. Binder jetting instead of paper uses a powder material, and then the binder is deposited in the 2D cross-section of the part being printed. After each layer, the build box is lowered and a fresh coat of powder is spread using a roller [14]. A variety of materials can be manufacturing into a powder form including metals, sand, glass, ceramics, and plastics. The loose powder acts as a support for the bound parts until the binder is cured. For metals and ceramics, a sintering heat treatment step is required to fuse the powder and obtain full mechanical properties. The largest complex 3D printed titanium part was printed using a ExOne M-Print binder jetting system [18]. Binder jetting of sand is used to print sand cores and molds for metal casting. Sand printing reduces the turnaround time for sand casting and eliminates hard tooling and the associated carrying costs [11]. Binder jetting is scalable and limited only by the size of the build box. For example, ExOne's Exerial sand printer can create molds and cores with a build volume of 2200 x 1200 x 600 mm [19].

2.1.4 Directed Energy Deposition

The AM process directed energy deposition (DED) uses a material in wire or powder form which is melted and deposited through a nozzle onto a particular surface. DED is more intricate and is used for repairs or to add extra material to an existing part. The material is melted by either laser, electron beam or plasma arc and the process closely resembles welding [14].

2.1.5 Powder Bed Fusion

Powder bed fusion has many titles including selective laser sintering (SLS), electron beam melting (EBM) and direct metal laser sintering (DMLS). Powder bed fusion resembles the binder jetting process but instead of binder being deposited, an energy source such as a laser or electron beam will selectively melt the powder feedstock on the basis of digital solid model [20]. Powders from a variety of material types can be used but the most common are polymers and metals [14]. The loose powder acts as a support allowing for complex part design although metal parts usually require supports to prevent part distortion due to residual stresses from the local heating. The aerospace industry is always trying to reduce the buy-to-fly ratio, which is the ratio between the raw material weight to the final weight of the component. With traditional manufacturing, the buy-to-fly ratio for aerospace engines and structural components can be 10:1 or as high as 20:1. AM, specifically, powder bed fusion, with the ability to produce near net shape products due to the laser power, speed and layer thickness, which ranges from 20 to 100 microns, can achieve a buy-to-fly ratio of nearly 1:1 [21]. The aerospace industry is using powder bed fusion to produce end-usable non-critical and critical parts. A study was conducted on producing a part with traditional manufacturing and selective laser melting (SLM), the results revealed the mechanical properties were similar and a 40 percent reduction in material was achieved. The study presents the overall effect of saving 100 kg of material is approximately $4.5M savings per aircraft [22]. Avio Aero, a GE business, used EBM to produce low-pressure turbine blades with titanium aluminide (TiAl), 50 percent lighter than nickel based alloy which is typically used to produce the part [12].

2.1.6 Sheet Lamination

Sheet lamination is the process of laying sheets of material down and bonded the sheets to form an object [12]. Three common sheet lamination technologies are laminated object manufacturing (LOM), selective deposition lamination (SDL), and ultrasonic additive manufacturing (UAM). The main differences are the materials used; vinyl for LOM, paper for SDL, and metal for UAM [14],[12]. Sheet lamination is not popular in the aerospace industry but did gain spotlight in 2006 at Utah State University where a student manufactured small satellites. Fabrisonic, the company owning the patent for UAM, has been working with Oak Ridge National Lab to create heat exchangers and with NASA on multiple projects including embedded sensors and fiber optics into metal parts to monitor the overall stress of a component [23], [24].

2.1.7 Material Jetting

Material jetting is an AM process that resembles 2D ink jet printing. The process deposits material droplets onto the build platform. Materials are usually photopolymers or wax-like materials used for investment casting [12]. The material, once deposited, is normally cured with an ultraviolet light [14].

2.2 Aerospace Materials

Over the years the aerospace industry has evolved and performance has improved due to advanced materials and manufacturing processes. In 2014, 680,000 tons of material was consumed in military and commercial aircraft industry. An estimated six pounds (lb) of mill material is needed for every one pound of material for the final product [25]. The industry is constantly discussing ways to reduce these numbers and come to a near net shape production process. Aerospace structures differ from other structures due to high demands for performance and light weight, the use of composite materials and the application of thin-walled constructions [26]. The following sections will discuss traditional manufacturing materials used in aerospace, AM materials being implemented and finally new AM materials under investigation.

2.2.1 Materials used in Traditional Manufacturing

Aluminum is one of the most common materials in aerospace. Aluminum is used in aerospace due to low density, good thermal and electric conductivity, and the material's relatively inexpensive price. To strengthen aluminum elements, such as manganese, silicon, copper, magnesium, or zinc are alloyed. One of the most common aluminum alloys in aerospace is 7075, which contains zinc [27]. Aluminum content in aircraft structures has steadily reduced, and some recent aircraft designs have only 20 percent of the aircraft weight is aluminum [28]. Aerospace industry specialist, Michael Standridge explains aluminum-lithium alloys are being selected instead of traditional aluminum due to "high strength, low density, high stiffness, damage tolerance, corrosion resistance, and weld-friendly characteristics" [28].

Other alloys used in aerospace include titanium alloys and titanium aluminide. Titanium has high strength properties along with high temperature and corrosion resistance. In the past years, titanium in commercial aircraft has increased by 10 percent weight [29]. Titanium is expensive and difficult to machine. Titanium is most commonly found in the aircraft engine [29]. Titanium aluminide is lighter than titanium but is more brittle. Titanium aluminide can retain strength and corrosion resistance to temperatures up to 1,112 F □.

Composite materials are on the rise in the aerospace industry. A composite material is defined as an arrangement of fibers of a resistant material which are embedded in a material with a much lower strength and stiffness [30]. Composites improve fuel efficiency due to the lightweight structure and the associated high tensile strength, compression, and corrosion resistance. Composite materials comprise 15 percent of the structural weight of a civil aircraft and more than 50 percent of the structural weight of helicopters and fighter aircraft [30]. When compared to metals, carbon fiber reinforced polymer (CFRP) has a lower buy-to-fly ratio of one and a half to one. Four percent of the total aerospace material demand contains CFRP but is said to increase by 6.5 percent per year [25]. When designed properly, carbon fiber composites are not only stronger than steel alloys but also 40-70 percent lighter [27].

2.2.2 Materials used in Additive Manufacturing

Additive manufacturing can use a variety of materials including polymers, metals, ceramics, sand, paper and composites [31], [32]. The type of material depends on the AM process producing the part. The AM materials for aerospace can be broken down into two main groups: polymers and metals.

Polymers are categorized as thermoplastics or thermoset polymers. The difference between the two is thermoplastics can be melted, cooled, and hardened repeatedly maintaining properties where thermoset polymers cannot [12]. Material extrusion printers commonly use thermoplastics as feedstock. ABS, polycarbonate (PC), nylon and PLA are materials used for prototyping. For the aerospace industry, a common functional material is the thermoplastic Ultem 9085 Aerospace offered by Stratasys. The material is flame retardant, has a high strength to weight ratio and is produced with strict procurement requirements which makes the material ideal for end-usable part production [33], [12], [34]. Other material extrusion materials being used in the aerospace include polyphenylsulfone (PPSF), high impact polystyrene, and polyethylene terephthalate (PET) [12], [34]. Polycarbonate is finding use as an aerospace tooling material for sheet forming operations [35].

The most common polymer used in powder bed fusion is polyamide (PA) but high-performance materials are also available, suited for the aircraft industry. PEEK HP3, offered by EOS, belongs to the group of polyaryletherketone (PAEK) and properties include: good strength, stiffness and chemical resistance, flame retardant and high fire, smoke and toxicity performance [12], [36], [37]. Companies such as; 3D Systems, Rinkak, Materialise, CRP Technology offer a variety of polymer powders for powder bed fusion manufacturing[12]. Polyetherketoneketone (PEEK) has been evaluated by an America Makes project team for aerospace applications [38].

The list of AM metal materials is constantly growing. In the 2016 Wohlers Report the list of AM metals include “tool steels, stainless steels, titanium, titanium alloys, aluminum alloys, nickel-based alloys, cobalt-chromium alloys, copper-based alloys, gold, silver, platinum, palladium, and tantalum” [12]. Metal feedstock is typically either powder or wire [39]. The high surface area to volume ratio of metal powders results in greater explosion hazards for certain reactive metals (i.e. titanium, aluminum, and magnesium) [40]. Appropriate handling and storage of such powders are necessary.

The suitability of a material for additive manufacturing varies by process. For example, laser powder bed fusion is a desirable process for aerospace applications due to its precision and near complete density upon building. However, the production of aerospace alloys of interest is challenging. 2000 series alloys with copper additions and 7000 series alloys with zinc addition are prone to hot tearing and cracking due to rapid solidification rates. As such, casting-type aluminum alloys containing silicon and magnesium additions are more commonly used in laser powder bed fusion AM although new approaches may address hot tearing issues [41].

Metal parts produced by AM can have different properties than conventional wrought materials; therefore, many studies are being conducted to determine the properties of metal AM parts which are critical in the aerospace industry. The ASTM International Committee F42 on Additive Manufacturing Technologies has published AM industry standards on titanium alloys Ti-6Al-4V and Ti-6Al-4V-ELI and nickel alloys UNS

N07718 and UNS N06625.Research on some AM systems concludes parts produced by AM can approach the same properties of parts produced conventionally, with some able to reach 100 percent density[12].

2.3 Applications Specific to Aerospace Maintenance and Sustainment

With multiple AM processes available, the aerospace industry is using the technology for many applications specific to maintenance and sustainment. The next sections will explore how the aerospace industry is currently using AM and the benefits to the evolving technology.

2.3.1 Prototyping

When AM was first developed in the 1980s the initial purpose was the production of prototypes known as rapid prototyping [42]. Although early AM prototypes were only suitable to demonstrate form (shape), as AM processes became more precise and materials became more stable fit prototyping became possible. Later, more functional and durable materials enabled functional prototyping where the prototype can perform the same role as a production part. Although end-use parts receive great attention, prototyping is still being utilized [43]. Fit prototyping is useful in aerospace maintenance and repair. For example, FRC Southwest used AM to create a fit prototype of a tub fitting reinforcement. Once fit was verified, the part was machined out of aluminum [44]. As CNC machining is time consuming, relatively labor intensive (especially for CNC programming), and may be capacity constrained, AM fit prototypes can prevent machining time and cost being wasted on incorrect geometry and dimensional tolerances.

For functional prototyping, AM allows rapid component testing and redesign within days. SelectTech Geospatial, an Air Force defense program, used material extrusion to produce the entire four-foot wingspan airframe for an Unmanned Aerial System (UAS). SelectTech was able to test the UAS in the air, identify physical failures, redesign, and print new parts out in the next day without the added costs of computer simulation and wind-tunnel testing. After the UAS had a successful flight and reached 200 feet, the next step is to be put into production for a carbon-fiber airframe [45].

NASA and SpaceX are both using AM for rocket engine prototyping. NASA is prototyping a functional completely 3D-printed rocket engine, allowing NASA to conduct test firings with reduced time and development costs. SpaceX is prototyping rocket engines specifically for the Raptor propulsion system, a powerful engine potentially to be used in future missions to Mars [46].

2.3.2 Tooling, Fixtures, Jigs

AM can reduce costs and time in the aerospace maintenance and sustainment though the fabrication of tooling, fixtures, and jigs. The benefits of this can be realized nearly immediately without having to wait for qualification and certification needed for AM end-use parts. For each aerospace vehicle, hundreds of fixtures, guides, templates and gauges can be printed with AM, which reduces cost and lead time by 60 to 97 percent [47],[48].

Military maintenance and sustainment organizations are taking advantage of this. Since 2006, the Naval Air Systems Command Fleet Readiness Center East Cherry Point (NAVAIR FRC East) has been supporting the fleet by using AM to create custom tooling

[49]. FRC-East has demonstrated material extrusion printed tooling for sheet metal press forming, sheet metal stretch forming, and composite layup tooling. [35] FRC-East used AM tooling to return a AV-8B to flight that was damaged during a hard landing at sea. Polycarbonate material extrusion tooling was used to press form sheet metal doublers required for the repair. [35]

The aerospace industry is also leveraging AM for tooling. Piper Aircraft produces many hydroforming form tools and drill fixtures with a material extrusion process. The traditional approach involved CNC machining of the tooling which required 4 hours of CNC programming. AM process planning only takes 10 minutes [47]. Advanced Composite Structures (ACS) is a company that repairs and produces low-volume composite parts for the aerospace industry. The company also moved from CNC machining to material extrusion to produce tooling. ACS identified 79 percent savings in cost and 96 percent savings in lead time [50].

Aerospace metal castings can also take advantage of AM tooling. Castings can have long lead times: often 10-12 months for aerospace castings [51]. Binder jetting is being used to create tooling for sand casting. In traditional sand casting a hard pattern is produced and sand is packed around the pattern to create the sand mold. A core box is used to create a sand core for interior channels within a casting. Sand molds and sand cores are temporary tooling. When removing a casting from the mold, the casting is broken out of the mold through mechanical force, shaking, or blowing [12]. When AM is used for core box fabrication, material scrap can be reduce 90 percent compared to traditional manufacturing [52]. Deloitte consulting states the benefits of AM sand casting are reduction in lead time and cost, improved functionality, and increased customization [52]. Using AM for casting tooling improves lead times.

2.3.3 Repair

In addition to producing tooling, AM is also being utilized for repair of aircraft engine parts. Turbine engine parts, blade, compressors, and housing parts are a few of the parts being repaired with AM. When a part is worn or broken, the part is normally scrapped and a new part would be purchased or manufactured, but with AM the lifetime of the part can be extended [33]. Parts are repaired by removing the damaged material area and reconstructing the part using the undamaged area of the part [53]. The value of implementing AM for repair is impacted by a variety of factors including inspecting the repair for defects, repairing the part in situ, faster and cheaper repair techniques, and the ability to restore the part back to the original form with the same mechanical properties [54].

The common AM process for repair is directed energy deposition. Optomec, a producer of production-grade 3D printers, has successfully repaired parts used in gas turbine engines with a directed energy deposition process called the Laser Engineered Net Shaping (LENS) system [33]. A worn bearing housing from a gas turbine engine, originally considered scrap, was repaired using the LENS system with Ti-6Al-4V. Repairing the housing was 50 percent the cost of buying new, and the lead time was decreased from several weeks to a few days [55].

Increasing the service life of aerospace parts by AM repair can sustain parts and decrease costs, BeAM repaired over 800 aerospace parts extending the life of the part from 10,000 to 60,000 hours [12].

2.3.4 End Usable Parts

Another application for aerospace and defense is the direct fabrication of end-usable parts. Instead of the investments and lead times associated with traditional tooling, the end-use part is directly printed. One of the most visible examples of an end-use metal AM parts for maintenance and sustainment has been NAVAIR's demonstration of a titanium link and fitting assembly for the engine nacelle on the V-22 Osprey aircraft [56] [57].

For example, Kelly Manufacturing Company, one of the world's largest manufacturers of aircraft instruments decided to use material extrusion as a replacement for sand casting for a toroid housing. "The lead time for 500 units has been shortened to three days from order to delivery of parts," Justin Kelly said, the KMC President, "In the aircraft world that's quick for certified production parts" [47]. Not only did AM reduce the lead time by 93 percent but also achieved tighter tolerances [47].

A study was conducted by Oak Ridge National Laboratory and Lockheed Martin on the Bleed Air Leak Detect (BALD) bracket, a bracket used in the engine of the Lockheed Martin's Joint Strike Fighter, using a metal powder bed fusion process. The study was conducted to identify the cost structure and mechanical properties associated with additively manufacturing the bracket. Results concluded AM technology could achieve consistent mechanical properties of traditional manufacturing. The study demonstrated a 33:1 buy to fly ratio could be reduced to nearly 1:1 [58].

Using AM for part production allows for complex designs leading to a reduction or elimination of assembly. Numerous aerospace and defense parts produced with traditional manufacturing are usually simpler parts assembled together [59]. Adhesives, pins, nuts, bolts, screws, and rivets are some of the parts used for fastening. Assembly introduces reliability concerns along with an expensive bill of materials [59]. It should be noted that in some cases, a part consolidation might require a re-certification of the part design and there might be a reluctance to expend such funds on a legacy system.

Layer-by-layer production can also enable complex designs where material is added only where needed to meet strength, stiffness, interface, or manufacturability requirements. This can lead to weight savings. For example, the SAVING Project, a group of seven organizations committed to AM, analyzed the benefits of AM by taking a conventional part, redesigning to save energy and weight and then analyzing the results. The study was executed on commercial airplane seat buckles. From traditional to additive, the seat belt went from weighing around 155g to 68g. Taking an Airbus A380 into consideration, 853 seats are on the plane, resulting in a total of 74kg weight saving and 3,300,000 liters of fuel saved over the plane's life expectancy [60].

General Electric (GE) demonstrated combining weight savings and part consolidation in metal aerospace parts. GE’s LEAP engine will soon include nineteen additively manufactured fuel nozzles. The nozzles were redesigned from a 20 part assembly to a single component with a reduction of weight by 25 percent. Not only are the nozzles lighter but are also more durable, five times stronger than the original design [61] [62]. GE is committed to the technology and has stated the company plans to manufacture up to 100k parts with AM by 2020 [8].

EADS Innovation Works and EOS joined up to do a research study comparing investment casting and direct metal laser sintering (DMLS). The part used was an Airbus A320 nacelle hinge bracket. EADS has set up new criteria where a part must pass nine technology readiness level processes before a technology can be qualified for use in production. Not only did the AM bracket pass the sustainability requirement but the bracket demonstrated weight savings. The hinge bracket weight was reduced by 10kg, CO2 emissions were reduced by 40 percent and the consumption of raw materials was reduced by 25 percent [63].

2.3.5 Spare Part Production

Many challenges with spare parts arise including the unpredictable demand and supporting previous generations of parts [43]. According to an Air Force Material Command document, planes can average more than 27 years in a fleet. By delaying the retirement of aircraft such as the A-10, the cost to maintain inventory is estimated $3.4 billion over the next five years [64]. Components of older aircraft are unavailable because suppliers are out of business. Reverse engineering is used to improve and re-manufacture parts no longer in production for the B-52 Stratofortress [65], [7]. Additively producing spare parts can be a solution to the challenges.

AM has the ability to make a dramatic impact in the aerospace supply chain. Many studies have been conducted to calculate the amount of spare parts for optimized lead time and cost. If an abundance of spare parts exists, there will be unnecessary inventory costs. Alternatively, if not enough spare parts are available, lead time will increase which increases aircraft downtime, essentially driving up delay costs [66]. AM enables the aerospace industry to deploy printers and materials at or near the place of need. A wide range of spare parts can be produced on demand saving money and time[31]. A 2015 online survey of 120 manufacturing professional showed 64 percent of the manufacturers expect AM will be used to produce obsolete parts in the next three to five years [67].

2.3.6 Fabrication at the point of need

Additive manufacturing can take place closer to the point of need. This allows on-demand time-critical production closer to aerospace operations. Instead of shipping large quantities and varieties of spare parts to an operational theater, raw materials can be shipped instead and the parts fabricated in theater. This provides significant logical benefits although the shipping, storage, and handling of reactive metal powders (i.e. aluminum, titanium, and magnesium powders) must be considered.

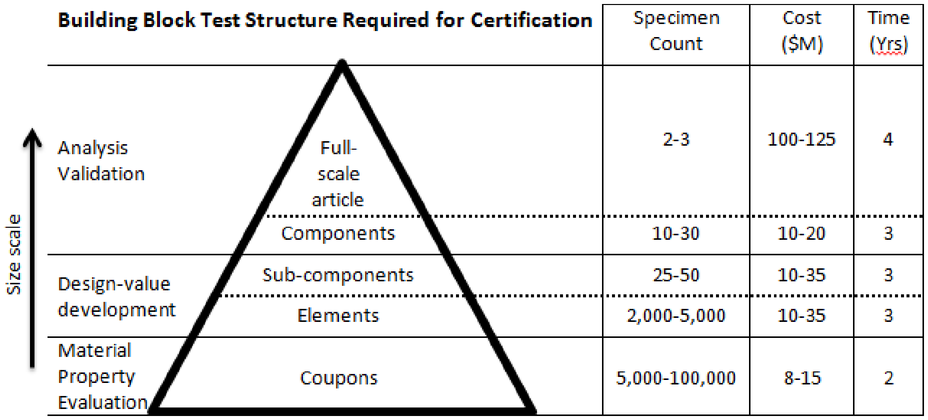
The U.S. Navy has demonstrated 3D printing at sea. One of the first demonstrations was held on a landing helicopter assault ship, the USS Essex (LHA-2). A Stratasys uPrint material extrusion printer was installed on the ship. Sailors designed non-structural replacement parts (i.e. deck drains and oil caps) as well as medical parts [44, 68]. Desktop 3D printers have been demonstrated on other warships including the carrier USS Harry Truman where Truman sailors designed a low cost clip [69]. The Naval Postgraduate School demonstrated a novel concept for on board fabrication. NPS pre-positioned UAV electronics on the USS Essex. They designed UAV structural parts on-shore and then transmitted the design files by satellite link to the Essex. The parts were printed and then assembled on the ship. The printed UAV was then flown [70]. One proposed concept of operations that builds on a strength of AM is the customization of UAVs for particular missions. Instead of storing parts for many types of UAVs, they would be 3D printed when a particular mission requirement is needed.

AM is also being used to produce tools and parts in space. The Made In Space printer was installed on the International Space Station (ISS) in November of 2014, normally the spaceflight crew would wait for weeks or months for a resupply mission to bring broken or lost tools, but with AM in space, the wait is over. Manufacturing in space can help with sustainment of long duration missions and human exploration [71]. Most recently, March 2016, the additive manufacturing facility (AMF) was installed on the ISS, which can manufacture larger and more complex parts [72]. Besides manned space flight, satellites could be printed and deployed on-orbit leading to a means of reconstituting satellite constellations that have degraded due to age, natural damage, or combat.

2.4 Qualification/Certification

The aerospace industry is regulated with qualification, certifications, and quality controls in order to ensure public safety. The qualification and certification process for aircraft components can cost over $130 million and can take up to 15 years [39]. AM was essentially developed for prototyping, so qualification/certification for prototyping was never a concern. However, a challenge for certification in the aerospace industry has become predominant due to the increase of implementing AM for the production of critical components [73]. A problem currently exists for AM since the process is relatively new, and consequently, has few qualifications or certifications of standards. Therefore many companies, organizations, and the government are investigating the creation of certification standards for a wide adoption of AM [74]. DARPA, America Makes and the Navy are a few of the organizations pursuing accelerated ways to qualify AM processes and parts [39]. A lack of standards exists in AM because 120 variables need to be controlled to produce stable and repeatable parts, material data is not comparable between companies, different process parameters exist between machines, repeatability of results is low, and few specifications exist to ensure a product is built as specified [10], [75].

The FAA established the Additive Manufacturing National Team (AMNT) in the expectation of collaborating with academia and government agencies to apply current FAA regulations to AM products and to develop guidelines to certify the safety of structures. Figure 1 below shows the "building block test structure" used by the FAA in the certification of aerospace structures. The figure displays costs associated with the certification of low volume products [73].



Building Block Test Structure Required for Certification		Specimen Count	Cost ($M)	Time (Yrs)
Analysis Validation	Full-scale article	2-3	100-125	4
	Components	10-30	10-20	3
Design-value development	Sub-components	25-50	10-35	3
	Elements	2,000-5,000	10-35	3
Material Property Evaluation	Coupons	5,000-100,000	8-15	2

Figure 1 - Building Block Test Structure [73]

For AM, an important step to process qualification is monitoring the AM machines for process errors vital to the component. Research has been performed on detecting defects while a metal AM build is in progress. Nassar (2014) states, during metal AM, defects can result from improper parameter selection and sensors can be used to track defects [76].

According to the National Institute of Standards and Technology (NIST), three different paths to qualification exist statistical-based, equivalence-based, and model-based qualification [77]. Statistical qualification includes extensive testing, costing millions of dollars and up to 15 years to complete, where model based qualification requires a smaller number of tests because physics-based models are developed [78]. A popular way to characterize AM test specimens and parts is through nondestructive evaluation (NDE), which evaluates the quality of the part through technologies such as x-ray, liquid penetrant or UV dye, ultrasound, and eddy current [73], [79]. NDE allows validation of new processes without compromising commitments of quality and safety [6]. To validate performance and capabilities of an AM machine a NIST AM test artifact, designed with specific geometries, can be printed [73].

FAA has certified a few AM parts for flying, GE Aviation's T25 sensor housing is an example. Not only does GE plan to put the part on 400 jet engines, but GE was able to design, prototype, produce and certify an AM part in four months, a remarkable lead time in the aerospace industry [12].

2.5 Business Models

Implementing AM can disrupt or completely change a company's business model. Literature concludes five critical components need to be satisfied to establish a business model: Value proposition, value creation, value delivery, value communication and value capture [80], [81]. AM needs to deliver on each of these components in order for the industry to invest.

Another AM business model includes a virtual trading system. A survey, on industry members, was conducted revealed high interest in a virtual trading system and examples of financial agreements included: annual subscription fee with unlimited sales and commission based on the quantity of sales [82].

A challenge to the AM business model is intellectual property rights of the 3D CAD or build file used to produce parts additively [83]. AM along with 3D scanning and reverse engineering allow downloading, modifying and sharing of the build files easy, comparable to the downloading music files for free, another digital disruptive development [84]. The issue is determining who owns the rights to the file and part and protecting the build file from being copied. A secure digital thread for AM will need to be developed and manage in order for both the supplier and customer to feel protected.

2.5.1 Digital Thread

AM allows anyone from anywhere to print parts as long as the digital design file is accessible. The AM build file or design file can be sent anywhere and printed out, comparable to a photo or written document that can be shared and printed in 2D. [31]. In order for AM to reach production level such as in traditional manufacturing, a digital thread needs established which is a series of complex, connected data-driven events [85]. A digital thread is a strand of data stretching from the initial design phase to the finished part and eventually to the end of the part lifecycle, containing all the information that enables the design, modeling, production, validation, and use and field monitoring of a manufactured part [85],[76].

The Air Force has been experimenting with a digital thread since the 1990s, not specifically for AM, but for system's entirety. David Walker, deputy assistant secretary of the Air Force for science, technology, and engineering emphasized specifications of a system are given but not monitored he believes industry needs to return to where understanding their systems are priority and digital models will be an enabler [86]. According to Deloitte Consulting, a successful digital thread for AM comprises of the ability to store and reference data, identifying a failed design or modification, and continuous improvement of products from data received from production [79].

The Smart Manufacturing Systems (SMS) Test Bed, was launched by researchers at the U.S. Commerce Department's National Institute of Standards and Technology (NIST) for the purpose of experimenting with the capabilities of a digital thread. The "innovation factory" is being utilized to track error, costs, production time, and quality. Researchers estimate 75 percent reduction in production lead time by converting to digital manufacturing [87].

A survey on the operational challenges for the Aerospace and Defense Industry was conducted by LNS Research. The survey was based on 300 respondents and the results are shown below in figure 2 [88].

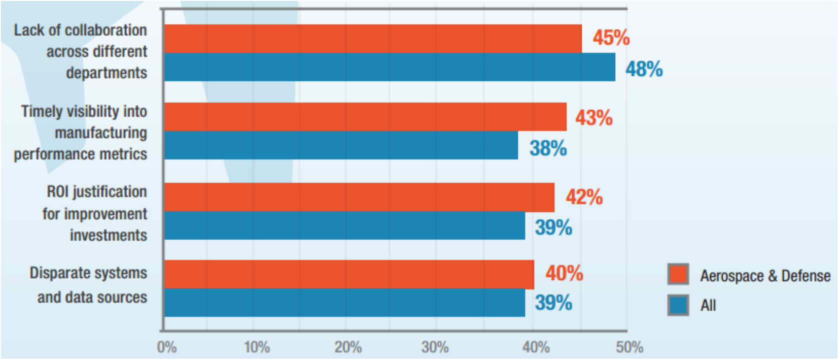


Figure 2 - Top Operational Challenges [88]

The study indicates eliminating operational challenges begins with communication and connectivity and the strategy would start with implementing a digital thread [88].

The Digital Manufacturing Design and Innovation Institute (DMDII) is in the process of creating a digital manufacturing commons. The goal is to form a digital thread connecting the manufacturing process from design and engineering to production and on to the supply chain. The goal is for the project to have 100,000 users nationwide by 2017 [89].

Chapter 3 Methodology

3.1 Survey

To better understand the expectations of both industry and government members and the assumptions they are making with respect to spare parts and the associated technical data package a survey was developed. The survey would aid in the correct development of the business models and what types of costs should be included. The survey was conducted using the website Survey Monkey. Two sets of questions were established, one for industry members and another for government members. The survey was sent via email to two groups familiar with the AM business model wargame and also had members of industry and government. The professional groups are:

- America Makes Maintenance and Sustainment Advisory Group (sent to the aerospace and defense members only)
- Department of Defense Additive Manufacturing Maintenance Operations Group

3.1.1 Government Survey

The government survey consisted of five questions

Government Question 1. Assume a supplier invested in the non-recurring costs during part development (i.e. design, tooling, qualification, etc.), when do you expect the supplier to obtain a return on investment (ROI)?

The following are the response options for Question 1:

RG1-1: Less than 2 years
RG1-2: 2-4 years
RG1-3: 4-6 years
RG1-4: 6-8 years
RG1-5: More than 8 years
RG1-6: Additional Comments

Government Question 2: Does selling price, of a spare part from a supplier, change depending on the quantity purchased, or is it a fixed price?

RG2-1: Yes, quantity determines selling price
RG2-2: No, selling price is fixed
RG2-3: Other (please specify)

Government Question 3: If you produced an additive manufactured part in house, who would pay for the qualification/certification costs?

RG3-1: Government

RG3-2: Industry

RG3-3: Please explain why

Government Question 4: Consider the situation where the government decided to produce spare parts organically (i.e. at a depot) using additive manufacturing instead of purchasing the spare part. If a supplier provided build files for government to additively produce parts in-house, what type of services would you expect to be included in the selling price? Check all that apply

RG4-1: 24/7 Helpline

RG4-2: Digital Rights Management (DRM)

RG4-3: Configuration management

RG4-4: Re-design services

RG4-5: Update file to more current file types

RG4-6: Build process updates for new AM technologies

RG4-7: Secure storage

RG4-8: Secure transmission

RG4-9: Field Service Representative (FSR)

RG4-10: Other (please specify)

Government Question 5: How much would you expect to pay for a single copy of a digital technical data package (TDP) file that would allow the government to print a single part?

RG5-1: $0-$500

RG5-2: $500-$2,500

RG5-3: $2,500-$5,000

RG5-4: Other (please specify)

3.2.2 Industry Survey

The industry survey was similar to the government survey but because the AM business model research being conducted is from the industry's perspective, a couple additional questions were inquired.

Industry Question 1: Consider the situation where the government decided to produce spare parts organically (i.e. at a depot) using additive manufacturing instead of purchasing the spare part. If your company decided to sell a digital technical data package (TDP) file to the government that would allow the government to print the part, what type of services would you expect to be included in the selling price? Check all that apply

RI1-1: 24/7 Helpline

RI1-2: Digital Rights Management

RI1-3: Configuration Management

RI1-4: Re-design Services

RI1-5: Update file to more current file types

RI1-6: Field Service Representative (FSR)

RI1-7: Secure transmission

RI1-8: Secure storage

RI1-9: Build process updates for new AM technologies

RI1-10: Other (please specify)

Industry Question 2: If your company incurred non-recurring costs during part development (i.e. design, tooling, qualification, etc.) of a part, when does your company expect to obtain a return on investment (ROI)?

RI2-1: Below 2 Years

RI2-2: 2-4 Years

RI2-3: 4-6 Years

RI2-4: 6-8 Years

RI2-5: More than 8 Years

RI2-6: Additional Comments

Industry Question 3: Does selling price of a spare part change depending on the quantity purchased, or is it a fixed price?

RI3-1: Yes, quantity determines selling price

RI3-2: No, selling price is fixed

RI3-3: Other (please specify)

Industry Question 4: Who would pay for the qualification/certification cost of a new additive manufactured part?

RI4-1: Industry

RI4-2: Government

RI4-3: Please explain:

Industry Question 5: How is profit determined in spare parts production?

RI5-1: Return on Investment (ROI)

RI5-2: Profit Margin added to cost

RI5-3: Other (please specify)

Industry Question 6: How many employees does your company have?

RI6-1: Under 50

RI6-2: 50-100

RI6-3: 200-300

RI6-4: 300-500

RI6-5: Over 500

Industry Question 7: How much would you expect to charge for a single copy of a digital technical data package (TDP) file that would allow the government to print a single part?

RI7-1: $0-$500

RI7-2: $500-$2,500

RI7-3: $2,500-$5,000

RI7-4: Other (please specify)

3.3 AM Business Models

The Department of Defense is exploring the potential of additive manufacturing (AM) to produce spare parts because of the benefits in reducing production lead time, the cost savings of producing spare parts at low production quantities, the reduction in warehouse costs, and the potential to produce organically (i.e. produced by the military instead of the commercial supply chain) at a depot or even in theater. The business models are developed based on the analysis of the business relationship between industry and government in a situation where industry has designed and currently produces a part, but the government itself wants to produce the same part as a spare part. The digital technical data package (TDP) becomes the transacted item industry provides to the government. Industry must now determine a way to maximize value in a situation where it might not be producing the actual spare part. Four business models involving the TDP and associated services are developed.

3.3.1 Business Model Assumptions

- The analysis is from industry's perspective. The intent is to incentive industry to provide data allowing the government to organically produce spare parts
- The industry member planned to produce spare parts therefore invested in tooling and/or design to produce the part.
- Models include one year prior production of spare parts produced conventionally.
- Industry had planned to re-coup a portion of the non-recurring costs (design, tooling, etc…) through spare parts fabrication.
- Models are based on a 15 year forecasted period.
- Government will incur the costs of AM qualification and certification. Those costs and any other government costs are not considered here.

3.3.2 Business Model Variables

In order to evaluate the business models, cost models will be developed with the variables defined in Table 1: Business Model Variables. The cost models will then be calculated to determine the total profit over 15 years. The survey conducted asked industry members how profit is obtained. The selections were either a return on investment (ROI) or profit margin. Due to there being two ways to obtain profit, each case study will have two different models based on how profit is obtained. The first profit model is based on 10% of the total costs the industry incurs while producing the spare part. The second profit model is based on a return on investment (ROI) in 2 years. These two ways to calculate profit are shown in Table 1 as Profit Margin and ROI Margin.

Two scenarios of the business model will be conducted. The first scenario is industry was producing spare parts using a conventional manufacturing process and the second is industry was already producing spare parts using additive manufacturing.

Table 1 - Business Model Variables

Cost Variable	**Unit**		**Comments**
Number of parts produced per year	(-)	N	
Non-Recurring Cost	($)	NR	Design / Tooling
Digital Services Cost	($/file)	D	Digital Thread/ 24-7 Help Line/Digital Rights Management
Profit Margin	(%)	PM	Based on Aerospace & Defense Profit Margin
ROI Margin	($/year)	RM	Based on Return on Investment (ROI) in 2 years
Part Cost	($/part)	P	Cost to Manufacture Part
Carrying Cost	($/year)	C	Based on 30% value of tooling/or material
Shipping Cost	($/year)	S	Based on calculations [90],[91]
Discount Rate	(%)	DR	Based on Aerospace and Defense Market
Period	(year)	Y	Assuming a 15 year period

3.3.3 Option 0: Conventionally manufactured spare parts

Option 0 is the business model based on the traditional spare parts model. This model is the original model the industry is using for spare parts production. Option 0 will be used as a reference to compare obtaining profit the traditional way versus Option 1-3. In the traditional spare parts model it is assumed that a 10% profit margin is also applied to the non-recurring costs since industry planned to recoup these costs with spare part production. Tooling cost associated with the manufacturing process is amortized within the first two years in Option 0. The tooling needed for the manufacturing process is assumed that it is a one-time purchase for the entire lifecycle of the part, due to low volume production.

Revenue and profit equations for Option 0 are shown below for both profit models

ROI Margin Model:

- Revenue/year (φ)

$$(P * N) + \frac{NR}{2} + C + S \qquad \text{(Equation 3)}$$

- Profit/year

$$\varphi - [(P * N) + C + S] \qquad \text{(Equation 4)}$$

Profit Margin Model:

- Revenue/year

$$C + S + (P * N) + [(NR + (P * N) + C + S) * PM] \qquad \text{(Equation 5)}$$

- Profit/year

$$[NR + (P * N) + C + S] * PM \qquad \text{(Equation 6)}$$

3.3.4 Option 1: One Time Sale of Complete Technical Data Package

Option 1 gives the government the opportunity to buy the technical data package of a part outright. The industry “wipes its hands” of the part, and now government will own all responsibility and rights of the part. Option 1 profit is calculated using the net present value (NPV) formula. NPV is used because the equation allows industry to calculate the worth of selling a part outright, by determining the future profits industry would have attained. For all models the non-recurring cost is amortized within the first 2 years of the 15 year period used in the NPV. Profit per year is based on an assumption of the quantity of spare parts sold. NPV is calculated similarly with either profit models. The discount rate utilized in this study is 8% based on the aerospace and defense market.

- Net Present Value

$$\sum_{y=1}^{Y} \frac{Profit_y}{(1+DR)^y} - NR \qquad \text{(Equation 7)}$$

3.3.5 Option 2: Cost per file per use

Option 2 allows for industry to continue owning the rights of the spare part. When the government wants to produce a part on demand using additive manufacturing, they will purchase a technical data package (TDP) file from industry. The file will be accessible for one build. After the part has been produced the build file is no longer available, if government wants to produce a second part, another TDP file will be purchased from industry. Included in the cost per file are digital services which will be determined from the business model survey results. Selling price per file is based on the digital service cost per file plus a profit margin.

Revenue and profit equations for Option 2 are shown below for both profit models.

ROI Margin Model:

- Revenue/year (φ)

$$(D * N) + \frac{NR}{2} \qquad \text{(Equation 8)}$$

- Profit/year

$$\frac{NR}{2} \qquad \text{(Equation 9)}$$

Profit Margin Model:

- Revenue/year

$$\{D + [D * PM]\} * N \qquad \text{(Equation 10)}$$

- Profit/year

$$[D * PM] * N \qquad \text{(Equation 11)}$$

3.3.6 Option 3: Annual Subscription Fee

Option 3 is similar to option 2 as it is a business model based on TDP file transactions. Option 3, however, is based on an annual subscription fee. The Industry will charge an annual subscription fee and the government can download an unlimited number of TDP files. The annual fee is determined by calculating the average quantity of files government will request per year and multiplying the number by the digital services cost per file. A profit margin is also added on to the annual fee.

Revenue and profit equations for Option 3 are shown below for both profit models.

ROI Margin Model:

- Revenue/year (annual subscription fee)

$$(D * N) + \frac{NR}{2} \qquad \text{(Equation 12)}$$

- Profit/year

$$\frac{NR}{2} \qquad \text{(Equation 13)}$$

Profit Margin Model:

- Revenue/year (annual subscription fee)

$$\{D * N + [(D * N) * PM]\} \qquad \text{(Equation 14)}$$

- Profit/year

$$\{D * N + [(D * N) * PM]\}\text{-}(D * N) \qquad \text{(Equation 15)}$$

3.4 Case Study Selection

To evaluate the effect each variable has on the different business models, several case studies are selected which include different aerospace parts produced with different materials.

3.4.1 Landing Gear

The first case study is selected from a journal research paper on developing cost models for additive manufacturing and comparing the costs to traditional manufacturing [92]. The research was conducted on a main landing gear of the Italian aircraft P180 Avant II by Piaggio Aero Industries pictured below [92].

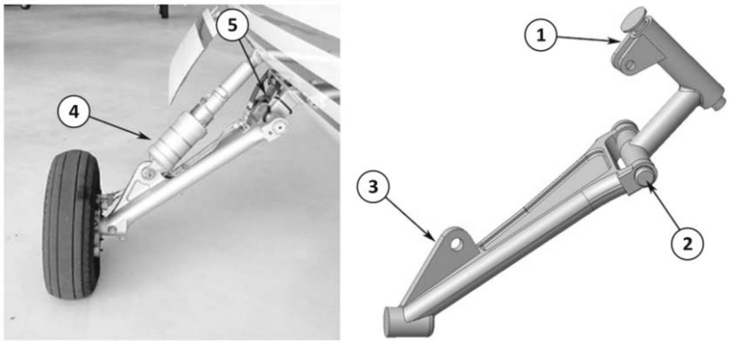


Figure 3 - Main Landing Gear [92]

In the study the landing gear was originally an assembled part produced by high-pressure- die casting (HPDC) and made from aluminum alloy (AlSi10Mg). The authors redesigned the part for additive manufacturing which allowed for the reduction of parts to one. The part was then produced with both HPDC and powder bed fusion and the costs of production were analyzed and compared.

For this thesis the cost models from the Atzeni and Salmi [92] paper are utilized, the HPDC cost model is summarized in Table 2.

Table 2 - HPDC costs adapted from Atzeni [92] (April 2017 EUR/$ exchange rate: 1.06)

Production Volume	pcs	N
Material cost per kg	$/kg	16.96
Part weight	Kg	0.162
Material cost per part	$	2.75
Standard components' cost	$	2014.00
Mold cavities and slides cost	$	16,324.00
Ancillary cost	$	3,922.00
Mold cost per part	$	22,260.00
Machine cost per part	$/h	275.60
Cycle time	H	0.001
Labor cost per hour processing	$/h	37.10
Percentage of operator time	%	10%
Processing cost per part	$	0.28
Heat treatment cost per part	$	1.51
Machining operations cost	$	14.82
Labor cost per hour post processing	$/h	26.50
Operator time	H	0.100
Post-processing cost per part	$	18.97
Wheel truck and major support total cost	$	22.00+22,260.00
Assembly cost	$	0.57
Total cost per assembly	$	22.57+22,260.00/N

The cost model for the AM method is on a powder bed fusion process and was updated to include the EOS m290 machine. Other AM parameters and costs were also updated. For EOS Aluminum (AlSi10Mg) is identified as $152 per kg [93]. From literature the depreciation time for the machine is 8 years and the utilization rate is assumed to be about 57% (5,000 hours) [94]. The machine cost was calculated to be $17.50/hr. Build time was calculated by using the build rate from the EOS material data sheet for AlSi10Mg which is 444 mm3/min [95] and 8.35 mm/s for the recoating speed which was found in literature [96] .

Table 3 - EOS m290 cost model adapted from Atzeni [92] (April 2017 EUR/$ exchange rate: 1.07)

Production Volume	pcs	N
Part Volume	mm3	66,420
Machine Parameters		
Layer Thickness	mm	0.03
Bulk Density of powder	g/mm^3	0.00267
Pre Processing time	h	1.2
Post Processing time	h	3
Depreciation	year	8
Costs		
Machine Cost	$/h	17.50
Machine Operator Cost	$/h	21.20
Material cost per kg	$/kg	152
Heat treatment cost per build	$	21.20
Build costs		
Material cost per build	$	107.82
Machine cost per build	$	770.65
Pre-processing cost	$	24.44
Post processing cost per part	$	84.80
Total cost per part	$	121.82

Once production cost of the part is determined a part demand needs established. A literature search was conducted in order to find a part demand over several years with high variability. Demand data was obtained from RAND National Research Institute for NIIN 012844013, an aircraft gas cold section module [97]. The demand rates are from 2003-2013. The average demand over the ten years was calculated to be 270 as well as a standard deviation of 44.

In order to evaluate how quantity affects profit, four different scenarios are established. The industry member has developed cost per file based on the quantity given from government. For the landing gear study, 270 files are needed per year. The industry developed a cost per file based on the specified quantity, and the cost is now fixed and does not change if the demand is higher or lower than the original demand. Three different demand variations are evaluated. All demand is calculated with a normal random distribution with a specified mean and standard deviation; using these variables a 15 year demand forecast is calculated. For each demand the standard deviation is 44, the first mean is 270 and the other two are 270 ± 88.

Not enough literature exists to determine the non-recurring costs associated with the landing gear; therefore the non-recurring costs will be varied. Similarly costs for digital services related to the digital thread were not found in literature so the digital services costs will also be varied.

Option 0-3 values

Non-recurring costs: \$10,000, \$100,000 and \$1,000,000

Tooling cost: \$20,000 (For HPDC)

Option 0 values

Carrying cost:

HPDC: $6,000 per year (30% of tooling cost)

EOS: $456 per year (30% of raw material cost, assuming 10 kg in stock)

Shipping cost:

HPDC: $411 per year

EOS: $600 per year

Cost to produce part based on 270 production volume:

HPDC: $22.57 per part

EOS: $ 121.82 per part

Option 2 and 3 values

Digital services cost per file: $250, $500 and $1,000

3.4.2 Yoke Cover

The next case study selected is a yoke cover currently being used at the 910th Airlift Wing in Youngstown, Ohio. The part was selected because of the extensive lead time associated with obtaining spare yoke covers.

Since access to the yoke cover itself is available, accurate data can be obtained. Therefore the costs and business models associated with the yoke cover are more precise than the landing gear case study. Youngstown State University students reverse engineered the yoke cover by 3D scanning with the 3D Systems Capture scanner. After the yoke cover was scanned, the Geomagic Design X software was used to modify the scanned data. The design time used in the study was 38 hours. The design time would be used to calculate the non-recurring cost for Options 0-3 associated with the yoke cover.

The yoke cover was traditionally manufactured by injection molding. The cost to produce the yoke cover with injection molding was calculated using an injection molding cost estimator from the website Custompart.net [98] . The costs to produce the yoke cover with injection molding are summarized in Table 4. The costs shown in Table 4 are for one half of the yoke cover, therefore the costs will be doubled to account for the entire part.

Table 4 - Injection Molding Costs for Yoke Cover [98]

Production Volume	(pcs)	N
Envelope X-Y-Z	in	3.14 x 2.95 x 59
Material cost per part	$	0.25
Production cost per part	$	2.4
Tooling cost	$	30,000/N

The AM process selected for the yoke cover study is material extrusion and the machine is the Fortus 900mc. The material selected is the thermoplastic, ULTEM 9085 Aerospace. To utilize the entire machine, the build is packed with 20 yoke covers, 20 top and 20 bottom pieces. The build time is calculated using the Fortus 900mc Insight and Control Center softwares. The parameters and costs associated with the Fortus 900mc and the production of the yoke cover are summarized in Table 5.

Table 5 - Fortus 900mc costs for Yoke Cover

Number of Parts	N	20
Machine Consumable Parameters		
Print Material used per build	mm3	1637723.2
Support Material used per part build	mm3	397877.91
Machine Parameters		
X Printable Dimension	mm	914.40
Y Printable Dimension	mm	609.60
Z Printable Dimension	mm	914.40
Layer Thickness	µm	254.00
Build Time	hr.	94.15
Pre Processing	hr.	1
Post Processing	hr.	2
Costs		
Print Material	$/cc	0.4536
Support Material	$/cc	0.4536
Support Removal Cost	$	25.00
Machine Cost	$/hr.	10.37
Machine Operator Cost	$/hr.	25.00
Build Cost		
Print Material Cost	$	742.94
Support Material Cost	$	205.49
Pre Processing Cost	$	25.00
Post Processing Cost	$	75.00
Machine Time Cost	$	976.57
Recurring Cost/ Build	$	2,025.00
Recurring Cost/Part	$	100.00

The 910th airlift wing provided an average annual demand of 2-5 yoke covers for 8 aircraft. The mean was calculated as 3.5 yoke covers for 8 aircraft and 0.4375 yoke covers are needed per aircraft. This was applied to the total fleet of 290 aircraft to find approximately 130 yoke covers are needed per year for the entire fleet. To calculate a standard deviation, RANDBETWEEN, was utilized in Microsoft excel and a random number was given between two and five for 15 years. The standard deviation of 1.06 was calculated from the 15 numbers. To apply the standard deviation to the total fleet of 290, 290 was divided by 8 to get approximately 36.25 and this number was multiplied by the original standard deviation in order to get a total standard deviation for the yoke cover mean of 130. The standard deviation was calculated to be approximately 38. The mean of 130 and standard deviation of 38 were then used in Microsoft Excel in the normal distribution function to calculate an estimated demand for 15 years. Similar calculations were conducted to achieve demand variations with the following mean and standard deviations: 92 ± 38, 168 ± 38.

Option 0-3 values

- Non-recurring costs: $30,000 (Design)
- Tooling cost: $60,000 (For Injection Molding)

Option 0 values

- Carrying cost:
  - Injection Molding: $18,000 per year (30% of tooling cost)
  - Material Extrusion: $2,055 per year (30% of raw material cost, assuming 10 canisters in stock)
- Shipping cost:

Injection Molding: $600 per year

Material Extrusion: $160 per year

Cost to produce part based on 130 production volume:

Injection Molding: $5.20 per part

Material Extrusion: $100 per part

Option 2 and 3 values

Digital services cost per file: $250, $500 and $1,000

3.5 Government Stocking Level Model

The business models developed are from the perspective of the supplier; the study will help determine what model allows the industry to still maintain a profit and what model can recoup the initial non-recurring costs the fastest. The research is being extended to also analyze the government's perspective of purchasing an AM machine and producing spare parts in house and on demand. The model will compare the government producing spare parts on demand using a traditional machine already existing in the depot and an AM machine. Lead time, cost and optimal quantity will be determined.

3.5.1 Case Study

In order to analyze a traditional vs. additive manufacturing cost model for the government, a part and machines need to be selected. For this study a traditional manufacturing machine typically found in a government depot location will be used. The machine selected is a CNC machining process. The machine parameter and costs for the CNC process are found in Manogharan et al. 2016. The additive manufacturing machine will be updated to a EOS m 290, however operating costs and other parameters will be adapted from Manogharan et al. 2016. The part selected for the case study is from Manogharan et al. 2016 and is shown in Figure 4.

Figure 4 - Part with CNC fixtures [99]

The material selected for this case study is the metal alloy Ti6Al4V.

3.5.2 Cost Models

The cost to produce the part for the CNC process was referenced from Manogharan et al. 2016. The equation is shown below:

Cost per unit = (volume of bar stock*cost of material) + (operating cost* (set up time+ hogging + roughing + finish time) + (cost of cutting tools * number of stages) [99]

The unit cost was calculated to be $1358.25 per part and a total processing time of 23.42 hours [99]. Indirect and machine costs were not included in the calculation of part cost; therefore the AM cost model will be developed similarly.

The AM cost model will use a similar approach to the calculations shown in Table 3. Material parameters are updated for Ti6Al4V and some costs are eliminated in order to remain consistent with the CNC cost model. Four parts are produced each build in order to reduce lead time and build cost. The costs are summarized below in Table 6.

Table 6 - EOS m290 cost model for part from **Manogharan et al. 2016 [99]**

Production Volume	pcs	4
Part Volume	mm3	69234.78
Machine Parameters		
Layer Thickness	mm	0.03
Bulk Density of powder	g/mm^3	0.00441
Pre Processing time	h	1.5
Post Processing time	h	20
Costs		
Operator Cost	$/h	104.00
Material cost per kg	$/kg	617.00
Build cost		
Material cost per part		519.01
Pre-processing cost	$	156.00
Post processing cost per part	$	2,080.00
Total cost per part	$	688.75

A variety of demand rates, production quantities and inventory stocking quantities will be investigated to compare the costs associated with producing the part traditionally and additively.

3.5.3 Optimal Stocking Level Model

In order to understand the effects AM in house production will have on the government, an inventory model is developed.

For the following model the CNC vs EOS m290 case study is implemented. Therefore the maximum number of parts built is four. A low demand rate is also assumed. At the beginning of implementing additive when a spare part is needed, there are no parts in inventory, production begins to produce four parts because it is cost efficient to fill build platform up when using additive, the time it takes to produce the four parts is P. At the end of production, the four parts are placed into inventory. T1, T2 and T3 represent the time it took for a spare part to be taken out of inventory. The reorder level in this example is assumed to be one, therefore when the inventory level reaches one part, production will begin, and to avoid stock out four parts will be produced. The maximum inventory level in this example is five parts. Figure 5 displays the inventory model.

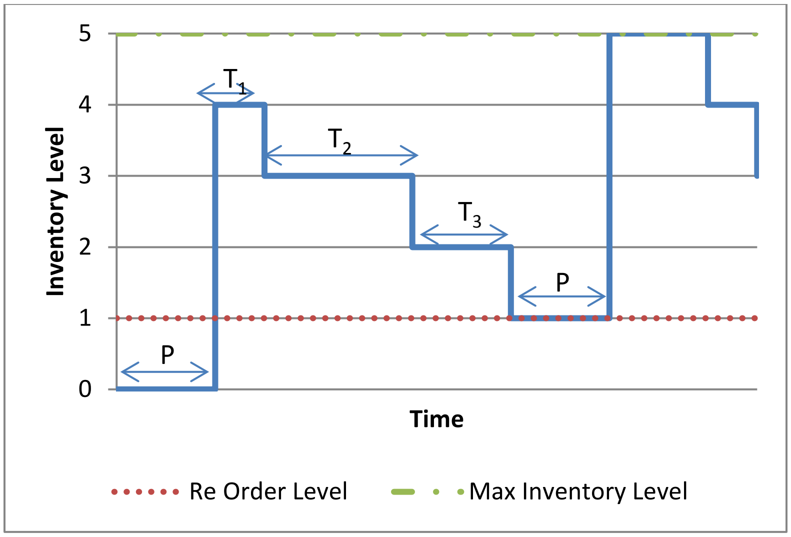


Figure 5 - AM Inventory Model

To calculate the optimal stocking level for the government, and the costs associated with inventory, the following equation is adopted [100]:

$$C(s) = h[s - (1 - p(s)\lambda\tau)] + \lambda\gamma p(s) \qquad \text{Equation 16}$$

Where $$p(s) = \frac{\lambda\tau^s}{s!} / \sum_{i=0}^{s} \frac{\lambda\tau^i}{i!}$$

The model is based on a (s-1, s) inventory model. The (s-1, s) inventory model represents the scenario where a certain stocking level is maintained and when a demand occurs for a part, the inventory level is replenished back to the specified stocking level. C(s) is the inventory cost determined by the stocking level s. The inventory carrying cost h is calculated from multiplying the inventory carrying cost rate by the cost to produce the part. The spare part demand (Poisson) rate is represented by $\boldsymbol{\lambda}$ and is per year. The lead time for producing the spare part is identified as τ years. If a stock-out would occur it would cost the government γ, which is 5% of the cost to produce the part. The probability of having zero units available in stock is represented by p(s). The goal is to find the optimal stocking level that will minimize the inventory cost.

Chapter 4 Results, Analysis and Discussion

4.1 Survey Responses

The business model survey had a total of 48 responses, 28 from government members and 20 from industry members. The results of the survey are grouped together by question, five questions were asked to both industry and government, and therefore the results will be compared. Industry members were asked two additional questions.

Question 1:

Assume a supplier invested in the non-recurring costs during part development (i.e. design, tooling, qualification, etc.), when do you expect the supplier to obtain a return on investment (ROI)?

Table 7 - Question 1 Responses

	Government	Industry
Less than 2 years	6	12
2-4 Years	13	7
4-6 Years	8	1
6-8 Years	1	0
More than 8 years	0	0

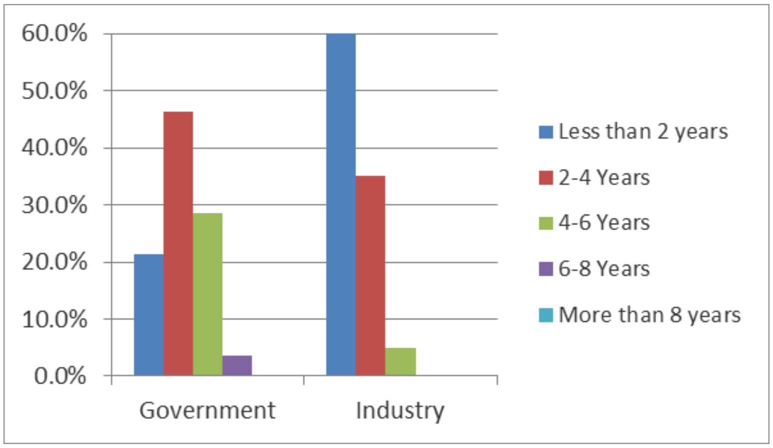


Figure 6 - Question 1 Results

Additional comments by government:

- “This will vary depending on size of investment and BCA results”
- “This is standard for stock held companies or those owned by a hedge fund (I'm a Reservist that used to work in manufacturing in private industry)”
- “Depends on the life of the weapon system the part is associated with”
- “This is directly dependent on the complexity and the resources invested in the Design - Test Phases”
- “ROI should be low due to less capital intensive equipment and allow small business to compete as suppliers for AM products/services.”
- “Military budgets in 5 year cycles called FYDP, therefore I would expect a ROI within the FYDP.”

- “Assumption is that an economical buy was executed for the effort.”
- “Assuming AM part development - the military is not ready for the large scale procurements that would be required for the supplier to obtain an ROI at this point”
- “Longer than that is too risky for a company unless they are getting a steady stream of external funding and investment.”
- “Are you speaking about amortization?”

Additional comments from industry:

- “It would be included with the first part unless there is a contracted number to buy.”
- “We will reverse engineer parts as a services contract for the government and deliver all technical data, 3D models and prototypes along with testing/ qualification date to our clients.”
- “Assumes no certification costs incurred”
- “It really depends on the nature and amount of the expense to give a better answer but I think 18 to 14 months is enough time to see a return.”
- “I am not involved in contract part development any more, but may be a AM purchaser in the future. I would expect payment terms to be within the contract, and at the latest, after final acceptance of the contracted development.”
- “Depends on platform and quantity. If there are international customers the ROI would be quicker.”

Question 1 discussion: From the graph and the comments the conclusion is a timeframe of more than four years is not acceptable for a return on investment from an industry standpoint. There does seem to be a difference between government and industry on how quickly ROI should be achieved. While 60% of industry participants expect less than two years ROI, only 20% of the government participants expect industry to achieve an ROI in less than two years. 46% of government participants expect a 2-4 year return on investment and one comment from a government participant suggested that an ROI within the timeframe of the FYDP was sufficient -- despite uncertainties in quantities that can occur during a FYDP including system cost increases or congressional reduction in funding. This difference in expectation could complicate a negotiation for data rights between the government and industry. The majority of industry members expect to see an ROI in less than two years therefore a two year ROI is selected for the business model analysis.

Question 2: Does selling price, of a spare part from a supplier, change depending on the quantity purchased, or is it a fixed price?

Table 8 - Question 2 Responses

	Government	**Industry**
Yes, quantity determines selling price	25	19
No, selling price is fixed	3	1

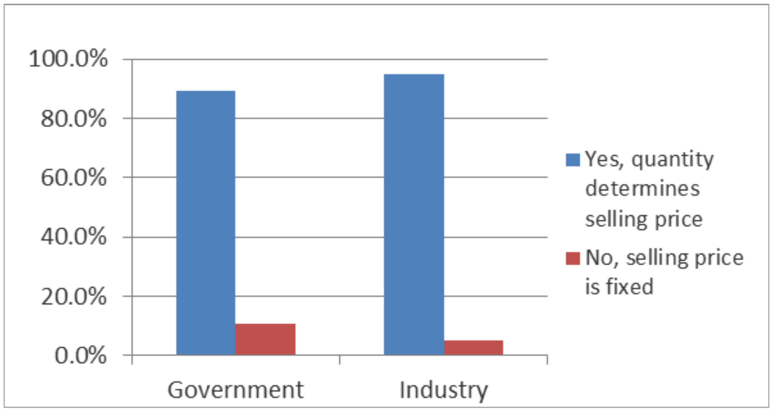


Figure 7 - Question 2 Results

Additional comments from government:

- “This again can be an either or...however, in general buying bulk of traditional manufactured processes items usually lends itself to cost reduction. AM is unknown”
- “This depends on the spare part and how it is manufactured. Most conventional manufacturing methods would typically exhibit volume ordering discounts.”
- “Selling price should be fixed by some outcome-based product support strategy (i.e. Performance Based Logistics). AM requires less tooling/set-up for low demand orders; small orders can still be profitable for supplier.”
- “However, the selling price should be in a reasonable ball park.”
- “Non recurring costs should be spread over the initial quantity acquired”
- “I know where you are going with this :-). With AM it wouldn't change nearly as much, but nevertheless, there should still be definitive quantity price breaks regardless.”
- “Yes, since volume defines the utilization rate of the processes. It drives business decisions.”

Additional comments from industry:

- “Amortized the non-reoccurring costs plus transaction costs”
- “Unless it is a reorder and no NRE is anticipated.”
- “We do not typically get involved with production - we are on the front end where we do the reverse engineering, drawing package development, 3D modeling and prototyping. Our price is for these services - and then we provide everything to

our client. When we are done we have qualified sources of supply and can provide estimates for production quantities for the asset(s).”

- “Selling price is fixed on a projected quantity. Some quantity would need to be contractual.”
- “Out of production, yes. Production no.”
- “Depends if we are the OEM and quantity.”

Question 2 discussion: The overall consensus is quantity does determine the selling price of a product. Many of the comments conclude price would be based on a specified volume. The results of this question helped determine how variation in demand would affect the business models. The business models developed used a specified estimated demand the government expected to need per year (270 for the landing gear, and 130 for yoke cover). The demand was used to calculate the selling price per part. Once the price was calculated, the price becomes a fixed firm price and does not change. Now if the demand changes per year, having a fixed firm price will allow for an analysis of the different models and how a demand variation affects the models.

Question 3:

If you produced an additive manufactured part in house, who would pay for the qualification/certification costs?

Table 9 - Question 3 Responses

	Government	**Industry**
Government pays	24	18
Industry pays	4	2

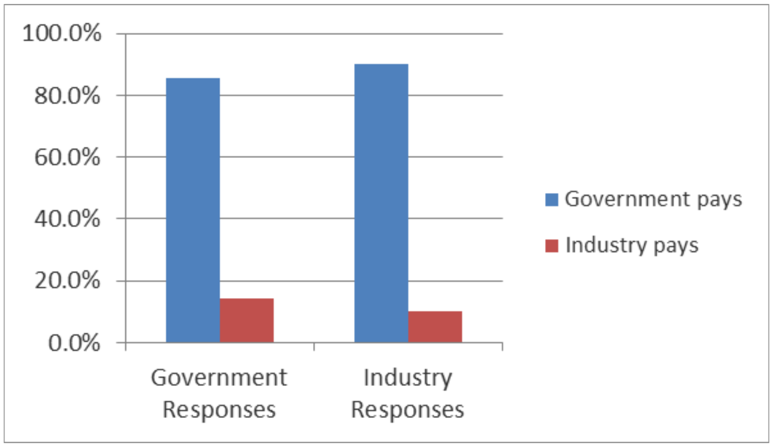


Figure 8 - Question 3 Results

Additional comments from government:

- "Ultimately the cost is passed to the government, either as a direct cost or as a built in cost masked as something else"
- "If the customer wants a service, government or not, you pay for that service"
- "In the long term, the government will not be in the business of paying for the qualification & certification of AM parts. However, the current state of the industry is such that widely publicized, statistically significant AM material properties (metal or polymer) plus the relevant industry standards are not available. Therefore, there are and will be instances where industry and government partner to achieve qualification & certification of a part, whether that be a point solution or a process solution."
- "Depends on complexity, critical risk to life and system and who owns the technical requirements the part complies with."
- "Work collaboratively with Advanced Research Labs"
- "Government should pay for what they use, especially if they produce an AM

part”

- “If the design is created by the government and the part is created by the government, the qualification responsibility would also lie with the government.”
- “Industry would provide inspection and acceptance points for Government test & acceptance. FAR 52.209-4 & 9.308-2”
- “It all depends on who is doing the work and where the requirement comes from. If industry looks at AM to supplement their Manufacturing needs, then they will pay for it. If the government is looking at AM to reduce Sustainment burden, then they will pay.”
- “Each should pay for their own; however, there should be good standards and guidelines to make this process easy and quick”
- “If the military additive manufactured a part, let’s say at a remote base. We would have little choice but to do the qual/cert ourselves at the forward base where it's printed.”
- “Part being done at an Organic Industrial base facility”
- “The Government is paying for it one way or another, whether done distinctly or rolled up. Especially if it is an engineering change, which many AM produced parts originally made via more traditional means would be, or if it were up front by design, the government would be doing it. After all, the government is determining whether the part is viable.”
- “Dependent on the type of qualification/certification. If this is airworthiness, then it is completely different story.”
- “If a new design AM part produced in house by the government on government

equipment, then of course the required qual/cert would be paid by the government."

- "In house is Govt in this case, so obviously we'd pay.
- "Only ones who can...unless the producer is the OEM"

Additional comments from industry:

- "Qualification / certification is part of the design process so the cost is paid for by the customer"
- "It would have to be built into the selling price paid by the government with any non-recurring costs from industry recouped over the quantity of parts purchased"
- "We typically do exactly this - paid for by the government and they own all data and rights at the end of our efforts."
- "End customer generally pays for certifications. They tend to see the largest benefits in price reduction."
- "The government has unique specs for the parts that they procure. Quals and certs would be based on their standards and specs."
- "The customer pays for the qualification of their part."
- "As the government would own the final timeline, I would expect that the qualification and final certification would be up to the end user."

Question 3 discussion: Both the government and industry participants agree that the government would pay for the qualification and certification costs to produce a part in house, 86% and 90% respectively. The cost of qualification and certification of a part is an expensive aspect of a business model, therefore determining who would be incurring the cost was highly important. The business models are developed from the industry's perspective, thus the qualification and certification costs are not included.

Question 4:

Consider the situation where the government decided to produce spare parts organically (i.e. at a depot) using additive manufacturing instead of purchasing the spare part. If a supplier provided build files for government to additively produce parts in-house, what type of services would you expect to be included in the selling price? Check all that apply

Table 10 - Question 4 Responses

	Government	Industry
24/7 Helpline	7	5
Digital Rights Management	19	15
Configuration management	11	12
Re-design services	9	11
Update file	17	12
Build process updates	15	3
Secure storage	12	13
Secure transmission	25	13
Field Service Representative	8	7

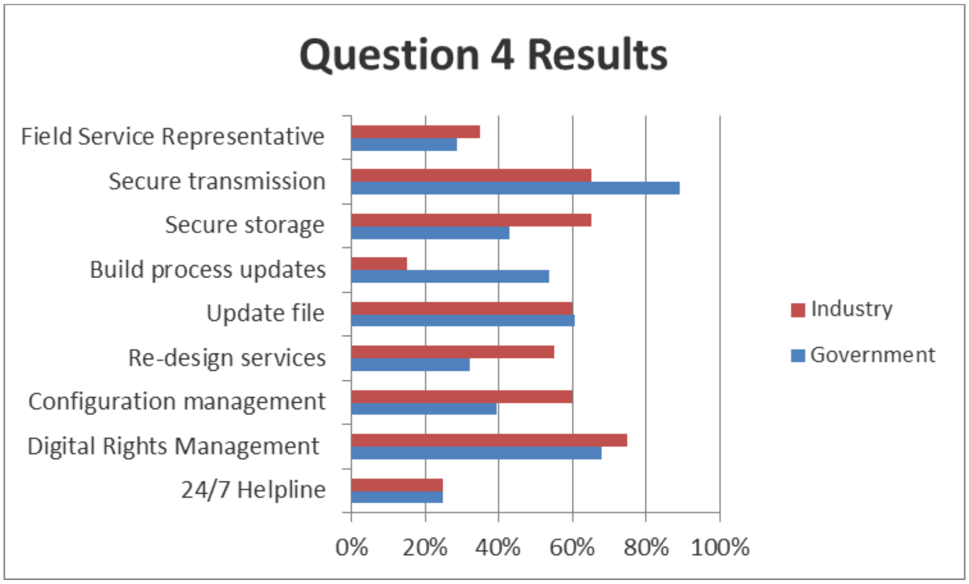


Figure 9 - Question 4 Results

Additional comments from government:

- “Government would never produce AM parts since there are no technical people with authority to approve a design.”
- “A lot of the above are standard engineering services”
- “Being able to manipulate the files is critical to fabrication”
- “Engineering support as needed. Doesn't necessarily have to be on site.”
- “Not necessarily a Help line, but do expect some help if necessary to understand the build file and the process it was intended for.”
- “Licensing costs whether per unit, batch, or one-time. But some of these items should be priced options, such as the Build process update. I can only imagine that would be needed if there's a configuration change to the machine, or if the machine itself goes obsolete.”
- “Dependent on Criticality of Item or Difficulty of item”

Additional comments from industry:

- “Re-design and update of file types may indeed be involved and offered as a service at additional cost TBD”
- “Prototype development and first article testing services”
- “Depends on the revenue stream. If a single purchase or non-reoccurring then no services after initial delivery. If reoccurring fee then services to maintain and upgrade product. Similar to software licensing agreements.”
- “NO guarantees the AM part will meet or exceed the durability of the current manufacturing process. (no adverse residual stresses that could cause distortion or premature fatigue)”

- “NO grantees the finishing processes will be identical and not adversely affect dimensional, corrosion or fatigue and fracture characteristics.”
- “ESA responsible for re-certifying the AM production part”
- “Some of these are infrastructure and would be expected of a reliable vendor. I assume the TDP would be encompass one product request, not a service contract. I checked only the ones for a specific request.”

Question 4 discussion: The question was formatted to allow participants select all types of services to be included in technical data package cost. 89% of the government participants selected secure transmission as a service and 65% of industry participants. Secure transmission is a critical component to both industry and government members as the technical data package is being transacted digitally and the protection of these files are priority. Only 15% of industry participants believe build process updates should be included in the TDP price, assuming the machines will not be updated frequently. 25% of both government and industry participants said a 24/7 helpline would be included in the file price, the result is lower than expected. The digital services cost included in the business models reflect the results of the survey.

Question 5:

How much would you expect to pay for a single copy of a digital technical data package (TDP) file that would allow the government to print a single part?

Table 11 - Question 5 Responses

	Government	**Industry**
\$0-\$500	2	0
\$500-\$2,500	4	1
\$2,500-\$5,000	4	1
Other (please specify)	18	18

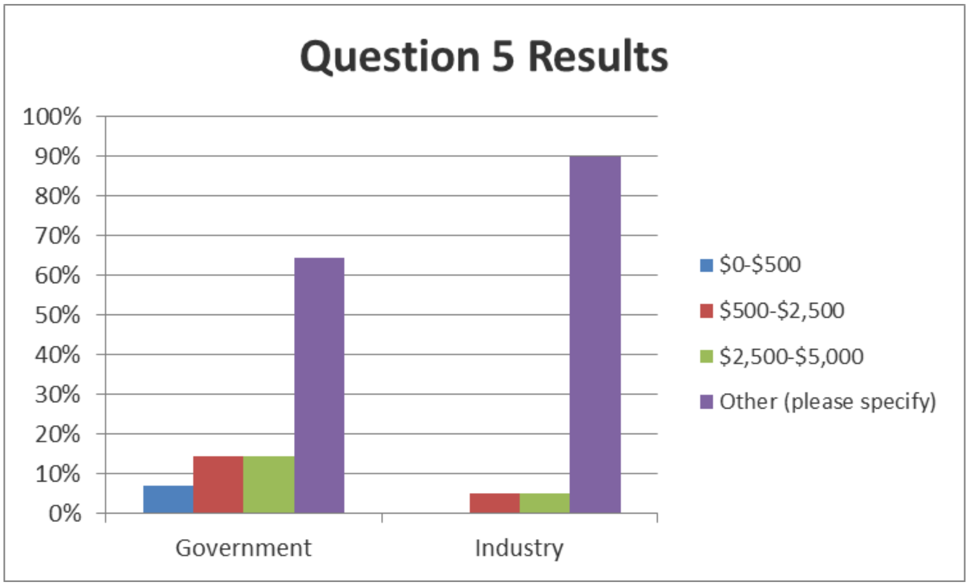


Figure 10 - Question 5 Results

Government comments:

- "This will vary drastically based on part criticality, needed OQE and number of expected parts that will be printed."
- "A complete TDP"
- "It really depends on whether the part is metal or polymer, the print time, material used, and the complexity of the part"
- "I have no clue."
- "Needs to be in relation to the total ROI for the part and parts design but significantly lower than the part cost"
- "Highly dependent on the part, but probably more than $5K for any structural or critical parts."
- "I think that depends heavily on the part size, material, complexity, post-processing, and level of criticality."
- "dependent up part complexity, therefore impossible to answer with limited data"

- “Depends on part cost”
- “It depends on complexity of the design. As a Government rep, I will not pay the same amount for the TDP of a bolt vs an Suspension component.”
- “All depends on the part, as price could vary greatly from a plastic door handle on a vehicle to titanium aircraft part and the amount of engineering that went into creating the TDP.”
- “Dependent on size, material, testing required. $125 - $1500”
- “Depends on the complexity of the part.”
- “Depends on the cost of the part. I would expect an o-ring to be MUCH less than a fuel pump for example.”
- “There is no way to quantify that w/o more information.”
- “Situationally dependent”
- “I think it depends on the engineering required to produce the design”
- “Depends on part and complexity”

Industry comments:

- “Depends on the value of the part. I would at least charge profit margin”
- “Depends on the certification/qualification cost and the quantity of parts ordered”
- “Will always vary based on the part.”
- “Every part/systems is different so we cannot quote a price without looking at a specific part or system.”
- “It depends on the complexity of the part”
- “Depends if the part is designed or off the shelf.”
- “Depends on the Question 1 guarantees.”

- “Don't know yet”
- “It depends on complexity of the part.”
- “There is no set price. It all depends on what resources it took to develop the part and the associated TDP”
- “Depends on the complexity of the TDP”
- “NA”
- “An honest answer would need some definition of the type, size, material, performance of part. The charge could be the entire range specified up to 20X more”
- “This question does not make sense in the format it is being asked. I would challenge the model where a company is 'selling' a TDP.”
- “It would depend on part and non-recurring investment.”
- “More detail would have to be specified around the scope included with the TDP to determine pricing”
- “It would depend on a number of factors”
- “Depends on the quantity...DRM would be in play.”

Question 5 discussion: Only ten government and two industry members selected a price range for the TDP. The other respondents selected “Other” and commented. The justification is the TDP price will reflect the complexity, criticality and other specifications of the actual part, since the survey did not give an example part, the participants could not conclude or give a range of the TDP price. Many factors contribute to the price, therefore business models will reflect the uncertainty and the price will be varied.

The following two questions, Question 6 and 7, were only addressed in the industry survey.

Question 6: How is profit determined in spare parts production?

Table 12 - Question 6 Responses

	Industry
Return on Investment (ROI)	2
Profit Margin added to cost	15
Other (please specify)	4

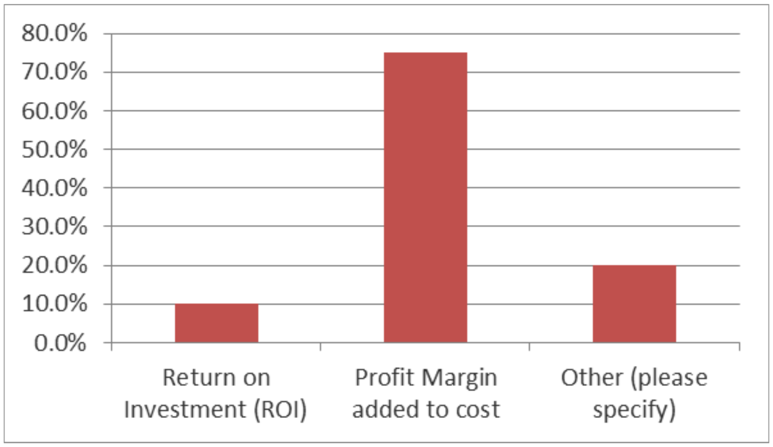


Figure 11 - Question 6 Results

<ins>Responses for "Other":</ins>

- "We do not make profit on parts - just on our services."
- "Unlike other industry (auto & appliance) after-market parts the defense industry is highly volatile. The defense supply chain needs to survive with other markets during the (extended) lean years. A predictable defense market for legacy parts is an important part to maintain the workforce skills and supply chain eco-system."
- "We do not share pricing information."

- "NA"

Question 6 discussion: The business models were originally developed using a return on investment to obtain profit in spare part production. After conducting the survey 75% of the participants concluded a profit margin added to the cost to produce the part is the used to achieve a profit in spare part production. Therefore the profit margin business model was added to the analysis. ROI profit margin business model is still included in the analysis but the profit margin added to the cost will be the focus of the business model analysis.

Question 7: How many employees does your company have?

Table 13 - Question 7 Responses

	Industry
Under 50	8
50-100	1
200-300	2
300-500	1
over 500	8

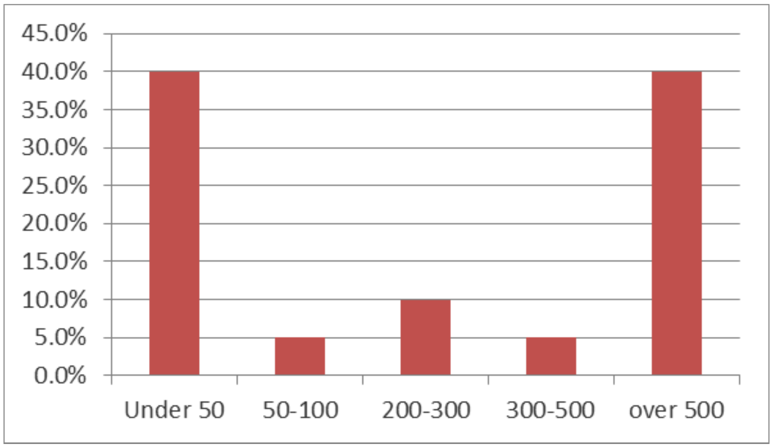


Figure 12 - Question 7 Results

Question 7 discussion: The majority of industry participants were either from small companies (<50 employees) or companies with greater than 500 employees, 40% of each.

4.2 Business Models

The objective was to calculate the total profit over 15 years and the time need to recoup the non-recurring costs for each Option (0-3) and compare the results. For each case study a ROI and profit margin model will be analyzed with the scenario that industry is producing spare parts with traditional manufacturing. From the survey results, profit margin is assumed to be the method industry utilizes to achieve profit; therefore the profit margin model for each case study will also be analyzed for the scenario where industry was already producing spare parts with AM.

4.2.1 Landing Gear

4.2.1.1 Landing Gear ROI Model Results

In order to calculate profit for the different demand variation scenarios, selling price for each option had to be calculated from the 270 fixed order quantity using equations 3, 8 and 12. Once selling prices are established the values become fixed firm selling prices regardless of the quantity of parts or files needed. Normal random distribution was used to calculate 15 different values that represent quantity per year for 15 years. Revenue per year is calculated by taking the quantity for the year and multiplying by the selling price. Profit for the year is then calculated by subtracting the costs for the year (not including non-recurring costs) from the revenue. Total profit for 15 years are summarized below in Table 7-9. Three tables exist, one for each non-recurring cost used. Tables also show the time needed to recoup the initial non-recurring costs.

Option 1 profits are based on the net present value calculation and are only calculated for the fixed quantity of 270 parts per year. The following lists the profits for Option 1.

Non-Recurring Costs \$10,000: NPV= \$98,392

Non-Recurring Costs \$100,000: NPV= \$393,568

Non-Recurring Costs \$1,000,000: NPV= \$3,345,334

The results conclude for each non-recurring cost, when the quantity is fixed, the profit for Option 0, Option 2 and Option 3 are equal. The reason is because each model calculates profit using a two year return on investment. For example, using 10,000 non-recurring cost, the profit is \$15,000 per year, including the additional tooling cost. To find the selling price \$15,000 is divided by quantity (270) and any additional costs are added on. Profit is then the subtracting the costs from selling price, which results in the ROI per year.

It becomes interesting when the demand is varied but selling price is fixed. For Option 2, digital service cost ends up not affecting the profit per year because the cost is added to the selling price but subtracted as a cost to calculate profit, therefore the cost is irrelevant. However for Option 3, the annual subscription fee is calculated by multiplying the digital service cost per file by the fixed quantity (270). The annual subscription fee does not change depending on quantity therefore the amount of files requested each year still costs the industry and affects the profit. The higher actual demand results in lower profit and lower actual demand results in higher profit.

Table 14 - Forecasted demand vs actual demand (ROI Landing Gear Results for NRC $10,000)

Total Profit 15 Years

Demand	Option 0	Option 2	Option 3		
			Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	$225,000	$225,000	$225,000	$225,000	$225,000
270 ± 44	$223,414	$223,889	$230,000	$235,000	$245,000
182 ± 44	$131,426	$159,444	$520,000	$815,000	$1,405,000
358 ± 44	$324,046	$294,389	-$87,250	-$399,500	-$1,024,000

Total Years to Recoup NRC

Demand	Option 0	Option 2	Option 3		
			Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	2	2	2	2	2
270 ± 44	3	3	2	2	1
182 ± 44	3	3	1	1	1
358 ± 44	2	2	>15	>15	>15

Table 15 - Forecasted demand vs actual demand (ROI Landing Gear Results for NRC $100,000)

Total Profit 15 Years

Demand	Option 0	Option 2	Option 3		
			Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	$900,000	$900,000	$900,000	$900,000	$900,000
270 ± 44	$895,081	$895,556	$905,000	$910,000	$920,000
182 ± 44	$609,759	$637,778	$1,195,000	$1,490,000	$2,080,000
358 ± 44	$1,207,212	$1,177,556	$587,750	$275,500	-$349,000

Total Years to Recoup NRC

Demand	Option 0	Option 2	Option 3		
			Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	2	2	2	2	2
270 ± 44	3	3	2	2	2
182 ± 44	3	3	2	1	1
358 ± 44	2	2	3	6	>15

Table 16 - Forecasted demand vs actual demand (ROI Landing Gear Results for NRC $1,000,000)

Total Profit 15 Years					
			Option 3		
Demand	Option 0	Option 2	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	$7,650,000	$7,650,000	$7,650,000	$7,650,000	$7,650,000
270 ± 44	$7,611,747	$7,612,222	$7,655,000	$7,660,000	$7,670,000
182 ± 44	$5,393,093	$5,421,111	$7,945,000	$8,240,000	$8,830,000
358 ± 44	$10,038,879	$10,009,222	$7,337,750	$7,025,500	$6,401,000

Total Years to Recoup NRC					
			Option 3		
Demand	Option 0	Option 2	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	2	2	2	2	2
270 ± 44	3	3	2	2	2
182 ± 44	3	3	2	2	2
358 ± 44	2	2	3	3	3

Total Profit Ratio vs Mean Quantity Analysis

An additional analysis was conducted in order to compare Option 1 profit with the other options total profit. The analysis will be used in each model and the yoke cover case study therefore will be referred to as the total profit ratio vs mean analysis. Mean quantities from 182-358 were selected and a normal random distribution over 15 years was applied for a total of 176 total profits. Non-recurring costs were subtracted from the total profit to give consistency with the NPV formula, which subtracts initial investments. These profits were then divided by the Option 1's net present value. A value is achieved which represents the ratio of total profit over 15 years over the profit obtained from selling the TDP at a one-time cost which is calculated using the NPV formula. A value greater than one means the option obtains a greater profit than Option 1, and a value lower than one signifies the total profit is less than Option 1. The analysis is summarized into line graphs to display the results with the ratio of the total profit/NPV on the y-axis and the mean quantity of data (or parts in the case of Option 0 on the x-axis. Three different graphs are shown below, one for each non-recurring cost.

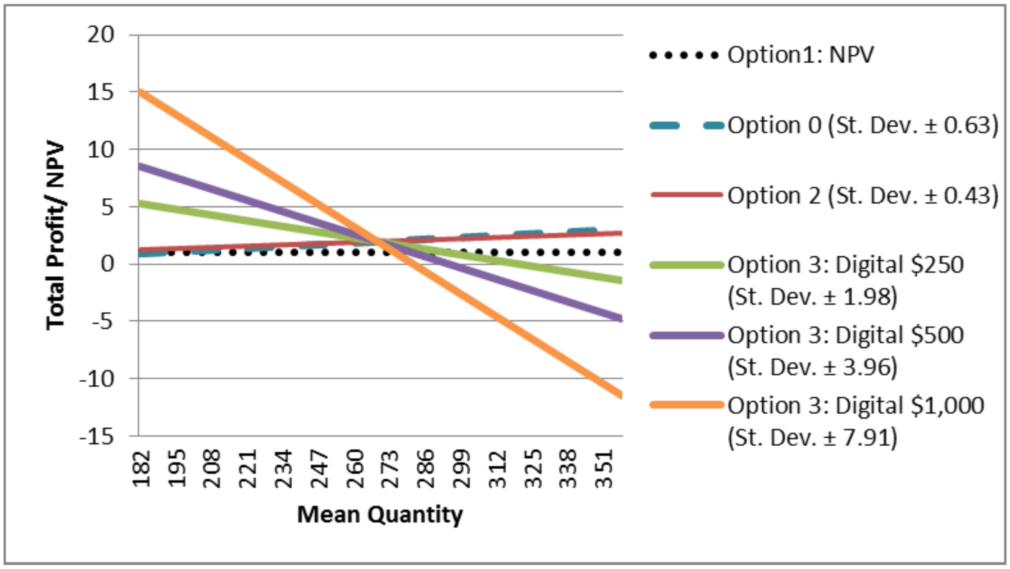


Figure 13 - Landing Gear ROI Model: Fixed Non-Recurring $10,000

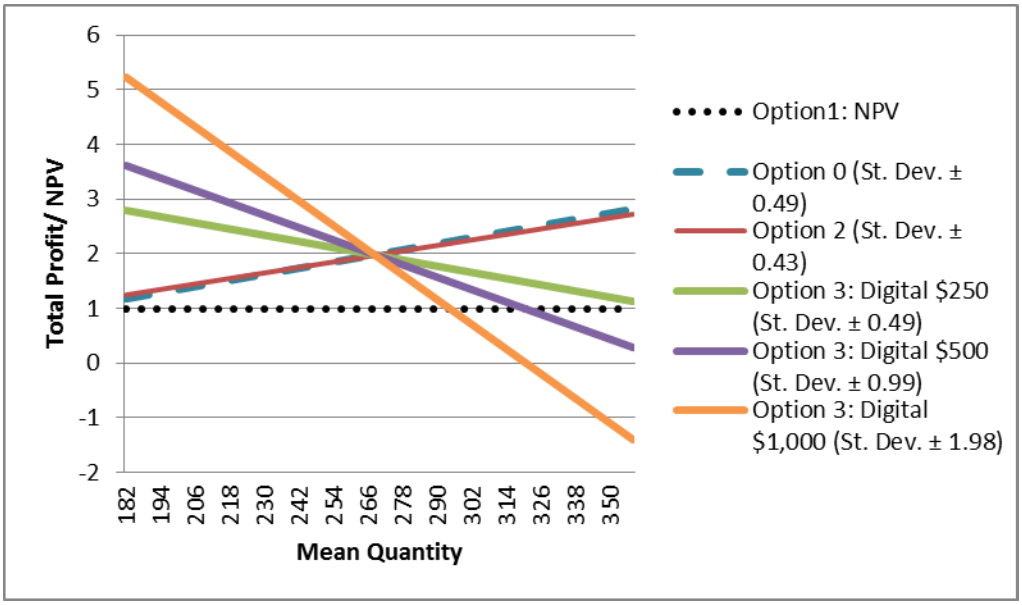


Figure 14 - Landing Gear ROI Model: Fixed Non-Recurring $100,000

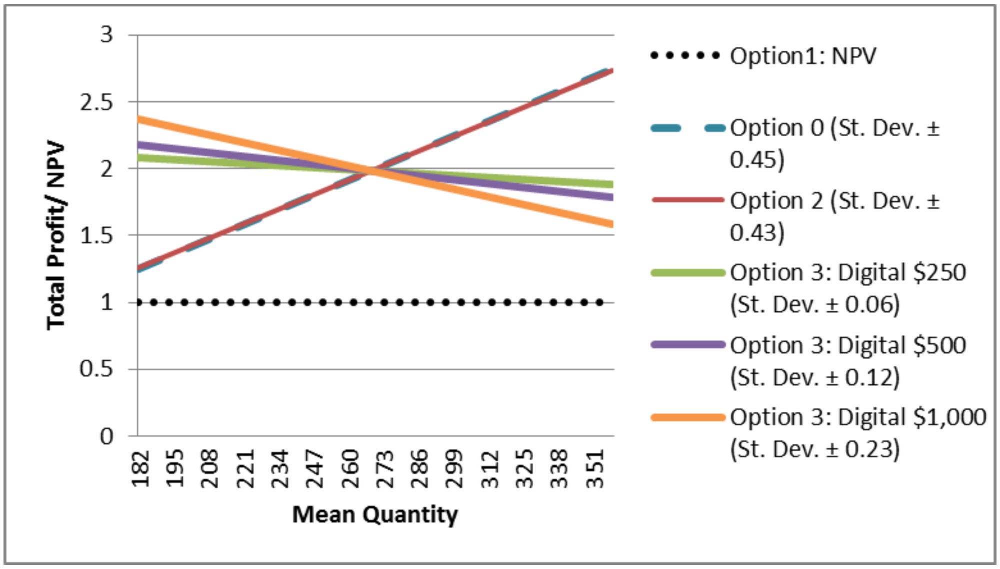


Figure 15 - Landing Gear ROI Model: Fixed Non-Recurring $1,000,000

For the ROI model, profit is obtained by calculating a return on investment within two years based on an anticipated quantity and using the amount to calculate selling price. When actual demand is greater than forecasted demand, sales on a per file basis (Option 2) will yield a faster return on investment and achieve a greater profit in Option 1 and 3. This is due to the cost per file model, the higher number of files sold will result in more profit coming in. When actual demand is less than forecasted demand, an annual subscription fee (Option 3) insures the industry partner will still obtain an ROI in two years and still achieve an equivalent profit that was expected. The reason Option 3 returns a greater profit for a lower demand is because the profit is based on the costs associated with industry to maintain and set up the digital services subtracted from the annual subscription fee. The annual subscription fee is a fixed price, therefore the lower the demand the less it costs industry to maintain the number of files. On the other hand, if a larger demand is requested, this will be expensive for industry to maintain and can result in a negative profit.

The ROI model profit margin per year is based on the non-recurring costs divided by two. Therefore, as seen in the graphs, the higher the non-recurring cost the more stable the results are for Option 2 and 3, meaning the profit is greater than the NPV profit. If an expensive non-recurring cost exists Option 2 or 3 should be selected based on a forecasted demand.

If an inexpensive non-recurring cost is present, Option 1 should be implemented and the industry partner can walk away with a profit similar to Option 0 and 2 with no further responsibilities and less risk than Option 3.

If industry wants to maintain the current profit level achieve through spare part production, Option 2 business model should be selected.

4.2.1.2 Landing Gear Profit Margin Model Results

Traditional Manufacturing

Selling prices were calculated using equations 5, 10 and 14 for Option 0, 2 and 3. Once the selling prices per part or per file are calculated for the specified quantity of 270, the price becomes fixed. The revenue for the profit margin model is obtained by adding the costs to produce the part or file plus an additional 10% margin of the costs. The margin changes according to the costs need to produce the specified quantity of parts or maintain the specific quantity of files. Compared to the ROI model, the profit margin model for the landing gear part has a lower profit along with longer returns in investment. The profit margin model will be analyzed in depth because, from the survey results, the method is commonly used in the aerospace industry. Three tables are shown below which display the total profit and time to recoup non-recurring costs for Option 0, 2 and 3. Four different demand variations are utilized. The profit totals in the tables do not include subtracting out the non-recurring costs.

Option 1 profit values are the following:

Non-Recurring Costs $10,000: NPV= $45,639

Non-Recurring Costs $100,000: NPV= $100,438

Non-Recurring Costs $1,000,000: NPV= $773,260

The results for NPV are lower profit for the Profit Margin Model compared to the ROI model. ROI model had a greater yearly profit which affects the NPV calculation.

Table 17 - Forecasted demand vs actual demand (Option 0 Landing Gear Profit Margin Model Results)

	Total Profit 15 Years		
Demand	Non-Recurring Cost $10,000	Non-Recurring Cost $100,000	Non-Recurring Cost $1,000,000
Fixed 270	$83,801	$218,801	$1,568,801
270 ± 44	$83,011	$217,345	$1,560,678
182 ± 44	$37,194	$132,860	$1,089,527
358 ± 44	$133,134	$309,768	$2,076,101
	Total Years to Recoup NRC		
Fixed 270	3	8	10
270 ± 44	3	9	11
182 ± 44	7	14	15
358 ± 44	2	5	8

The results for Option 0 shows a lower profit when the actual demand is below the forecasted demand and a higher profit is achieved when the actual demand is above the forecasted demand. The higher the non-recurring cost results in a higher profit however the return on investment is longer.

Table 18 - Forecasted demand vs actual demand (Option 2 Landing Gear Profit Margin Model Results)

	Total Profit 15 Years		
Demand	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	$101,250	$202,500	$405,000
270 ± 44	$100,750	$201,500	$403,000
182 ± 44	$71,750	$143,500	$287,000
358 ± 44	$132,475	$264,950	$529,900
	Total Years to Recoup NRC ($10,000)		
Fixed 270	5	3	2
270 ± 44	5	3	2
182 ± 44	6	3	2
358 ± 44	3	2	1
	Total Years to Recoup NRC ($100,000)		
Fixed 270	>15	9	5
270 ± 44	>15	10	5
182 ± 44	>15	13	6
358 ± 44	14	7	4
	Total Years to Recoup NRC ($1,000,000)		
Fixed 270	>15	>15	>15
270 ± 44	>15	>15	>15
182 ± 44	>15	>15	>15
358 ± 44	>15	>15	>15

Table 19 - Forecasted demand vs actual demand (Option 3 Landing Gear Profit Margin Model Results)

	Total Profit 15 Years		
Demand	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	$101,250	$202,500	$405,000
270 ± 44	$106,250	$212,500	$425,000
182 ± 44	$396,250	$792,500	$1,585,000
358 ± 44	-$211,000	-$422,000	-$844,000

	Total Years to Recoup NRC ($10,000)		
Fixed 270	5	3	3
270 ± 44	2	2	1
182 ± 44	1	1	1
358 ± 44	>15	>15	>15

	Total Years to Recoup NRC ($100,000)		
Fixed 270	>15	9	5
270 ± 44	>15	5	2
182 ± 44	5	3	1
358 ± 44	>15	>15	>15

	Total Years to Recoup NRC ($1,000,000)		
Fixed 270	>15	>15	>15
270 ± 44	>15	>15	>15
182 ± 44	>15	>15	10
358 ± 44	>15	>15	>15

The results for Option 2 and 3 are similar in the aspect of how they behave. Option 2 and 3 total profits are not affected by the non-recurring costs; therefore only one set of profits are displayed. The total years to recoup the non-recurring costs are dependent on the non-recurring costs which are displayed for each variation.

Option 2 resembles the traditional model (Option 0) as for each model a profit is obtained for every part or file sold. However, Option 2 results in a lower total profit than Option 0 when the non-recurring cost is $100,000 and $1,000,000. The data suggests Option 2 achieves higher profit than Option 0 when low non-recurring costs exist. Industry can insure a greater profit by increasing the digital services cost which increases the profit per file.

When the quantity is fixed annually, Option 2 and 3 return the same total profit because the annual subscription fee for Option 3 is based on the cost for digital services plus ten percent of the cost. This calculation is identical to Option 2, however when the demand begins to vary, Option 3 revenue stays the same but the digital services cost increases for a higher demand and decreases for a lower demand, which results in a different output than Option 2. Industry risks losing profit if the demand is higher than the forecasted demand. Industry should only implement Option 3 if there is little to none variation in the demand for the spare part.

Profit Margin Needed for 2 Year ROI

The profit margin models were further analyzed in order to calculate the specific profit margins required to achieve a two year ROI. The Goal Seek application in Excel software was used to calculate the profit margins. Goal Seek cycles through all possible profit margins until the profit for year two returns the specified non-recurring cost. This method was performed for all Options with all three non-recurring costs. Figures 16-18 show the profit margins needed to obtain $10,000, $100,000 and $1,000,000 within two years.

Table 20 - Profit Margin for 2 Year ROI ($10,000) - Landing Gear

Demand	Option 0	Option 2 $250/file	Option 2 $500/file	Option 2 $1,000/file	Option 3 $250/file	Option 3 $500/file	Option 3 $1,000/file
270 fixed	12%	22%	11%	6%	22%	11%	6%
182 ± 44	23%	32%	16%	8%	-8%	-19%	-24%
270 ± 44	18%	27%	14%	7%	4%	-7%	-13%
358 ± 44	7%	18%	9%	5%	43%	32%	26%

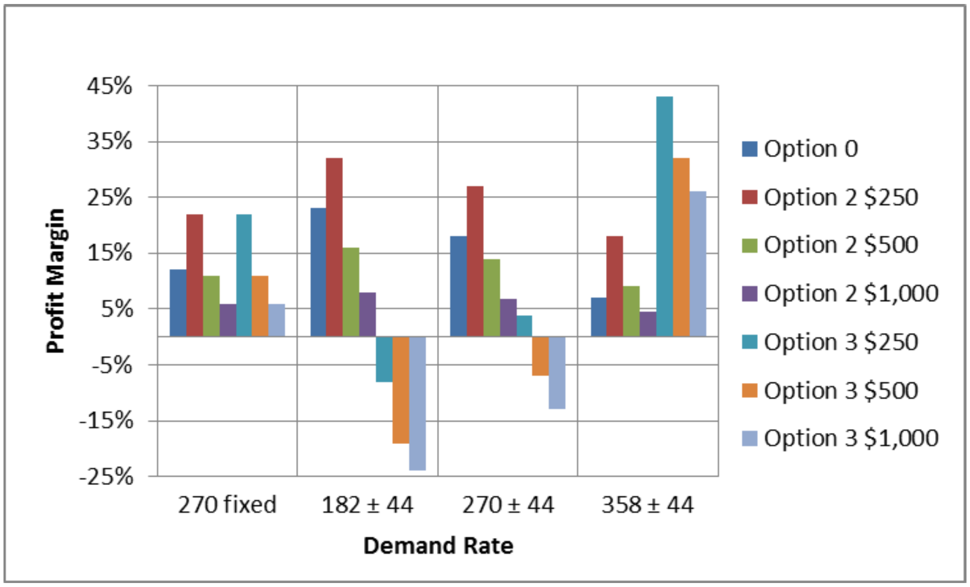


Figure 16 - Profit Margin for 2 Year ROI ($10,000) - *Landing Gear*

Table 21 - Profit Margin for 2 Year ROI ($100,000)-Landing Gear

Demand	Option 0	Option 2 $250/file	Option 2 $500/file	Option 2 $1,000/file	Option 3 $250/file	Option 3 $500/file	Option 3 $1,000/file
270 fixed	30%	89%	44%	22%	89%	44%	22%
182 ± 44	45%	127%	63%	32%	59%	14%	-8%
270 ± 44	47%	109%	54%	27%	71%	26%	4%
358 ± 44	24%	74%	37%	18%	109%	65%	43%

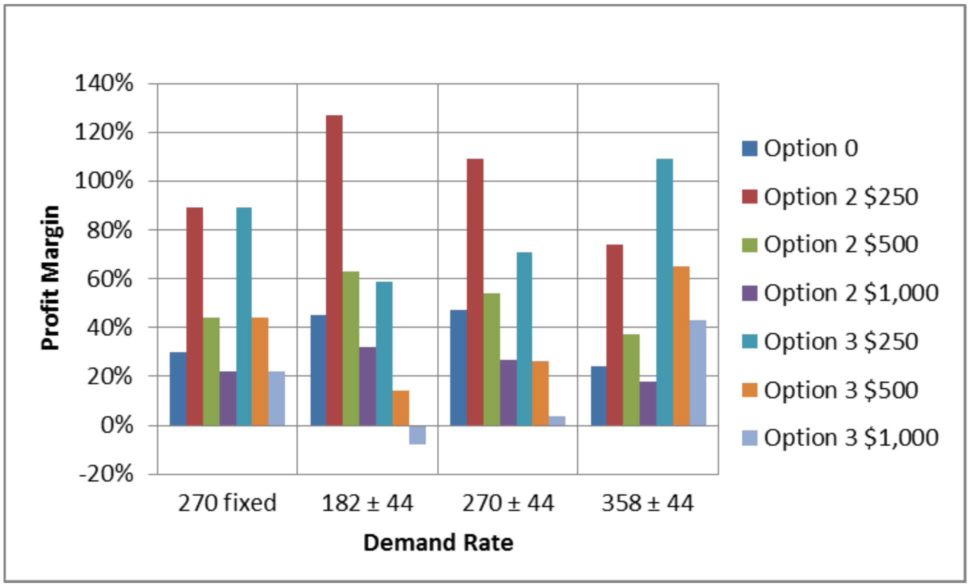


Figure 17 - Profit Margin for 2 Year ROI ($100,000)-*Landing Gear*

Table 22 - Profit Margin for 2 Year ROI ($1,000,000) - Landing Gear

Demand	**Option 0**	**Option 2 $250/file**	**Option 2 $500/file**	**Option 2 $1,000/file**	**Option 3 $250/file**	**Option 3 $500/file**	**Option 3 $1,000/file**
270 fixed	47%	756%	378%	189%	756%	378%	189%
182 ± 44	68%	1079%	540%	270%	726%	348%	159%
270 ± 44	58%	925%	463%	231%	737%	359%	171%
358 ± 44	39%	627%	313%	157%	776%	398%	209%

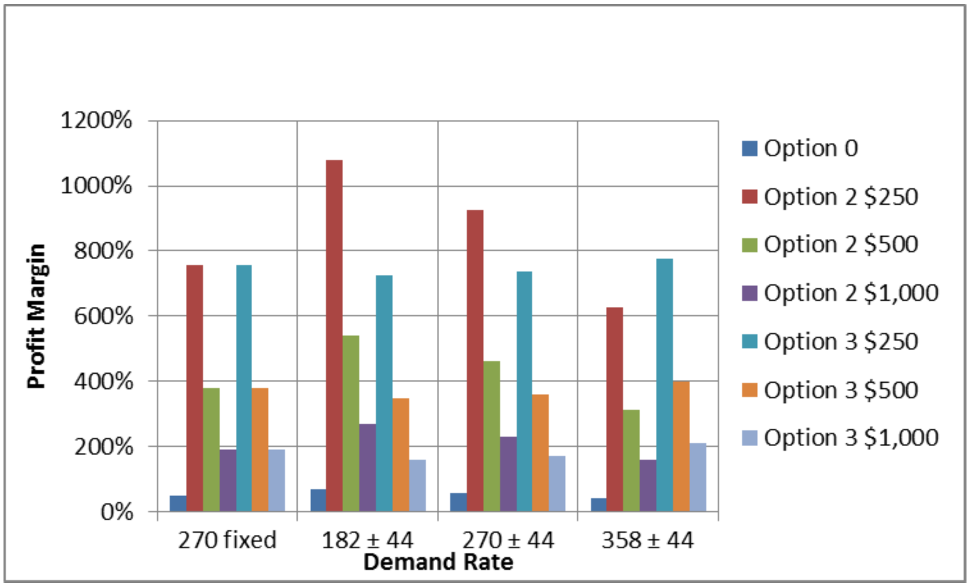


Figure 18 - Profit Margin for 2 Year ROI ($1,000,000) - *Landing Gear*

Figure 16 - 18 conclude a higher non-recurring cost will need a higher profit margin in order to achieve a 2 year ROI. For Option 2 it can be concluded the lower the digital service cost a higher profit margin is required. Also for Option 2 as the demand rate increases, the profit margin decreases. On the contrary, Option 3 requires a lower profit margin for lower demand rates. Option 3 exhibits negative profit margins for low demand rates with a lower non-recurring cost. The annual subscription fee is based on 270 files, therefore when the demand is extremely low, low costs exist and the annual fee returns a higher profit for industry.

Total Profit Ratio vs Mean Quantity Analysis

Similarly to the ROI model, total profit ratio vs mean quantity graphs were plotted. Three graphs are shown below, organized by increasing non-recurring cost. As the non-recurring costs increase, the overall total profit decreases.

For Option 2, since the model is a cost per file per use model, the more files purchased, the higher the total profit is, which can be seen in all of the graphs. Also, the higher the digital service cost, the higher the profit for Option 2.

For Option 3, results are quite the opposite. Option 3 is based on annual subscription fee. The government pays for the annual fee and can request as many TDP files as needed. However, for industry, a higher demand equals higher costs to store, maintain, and transmit the files. Industry starts to lose money when the annual subscription fee does not cover all of the costs due to an unexpected high demand. From the graphs the conclusion is, a lower actual demand yields a higher profit and a higher actual demand yields a lower profit. The digital services cost affects the total profit for Option 3 in an interesting way. From a mean quantity between 182 to approximately 290 the higher the digital service cost the higher the profit. A mean quantity of 290 to 358, the lower the digital services cost the higher the profit, but the line is lower than one, meaning the NPV profit (Option 1) is has a greater profit.

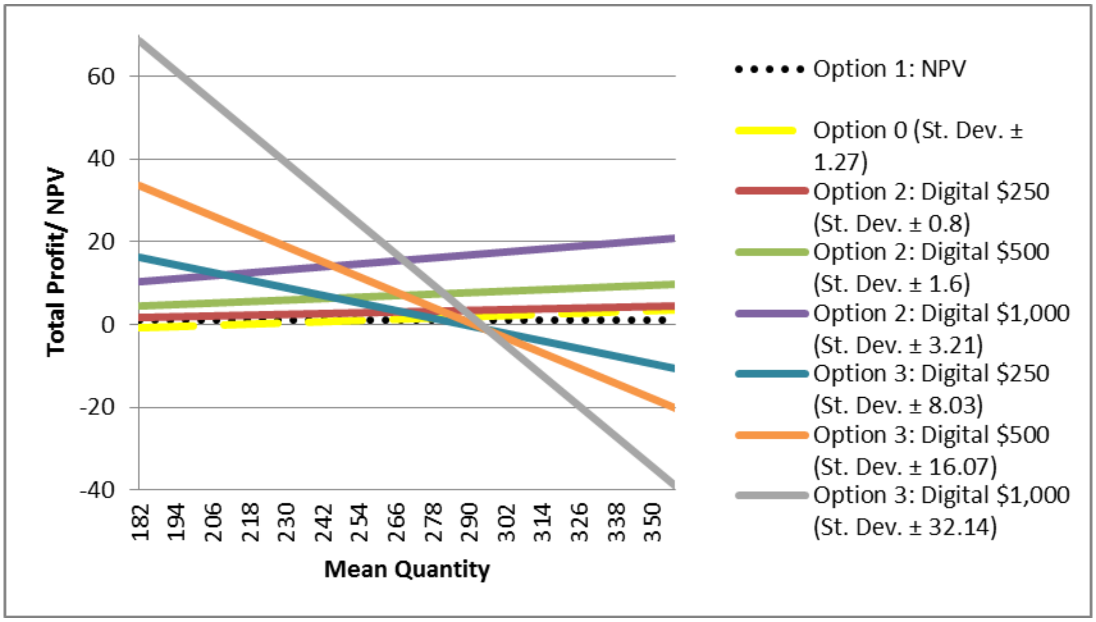


Figure 19 - Profit Margin Model, NRC $10,000- *Landing Gear*

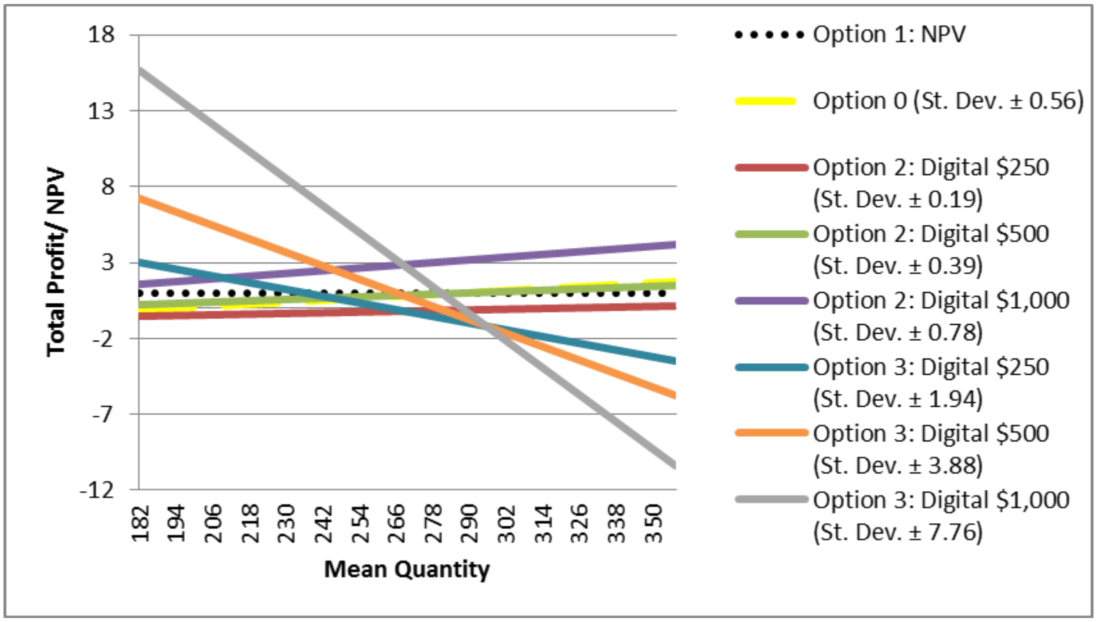


Figure 20 - Profit Margin Model, NRC $100,000- *Landing Gear*

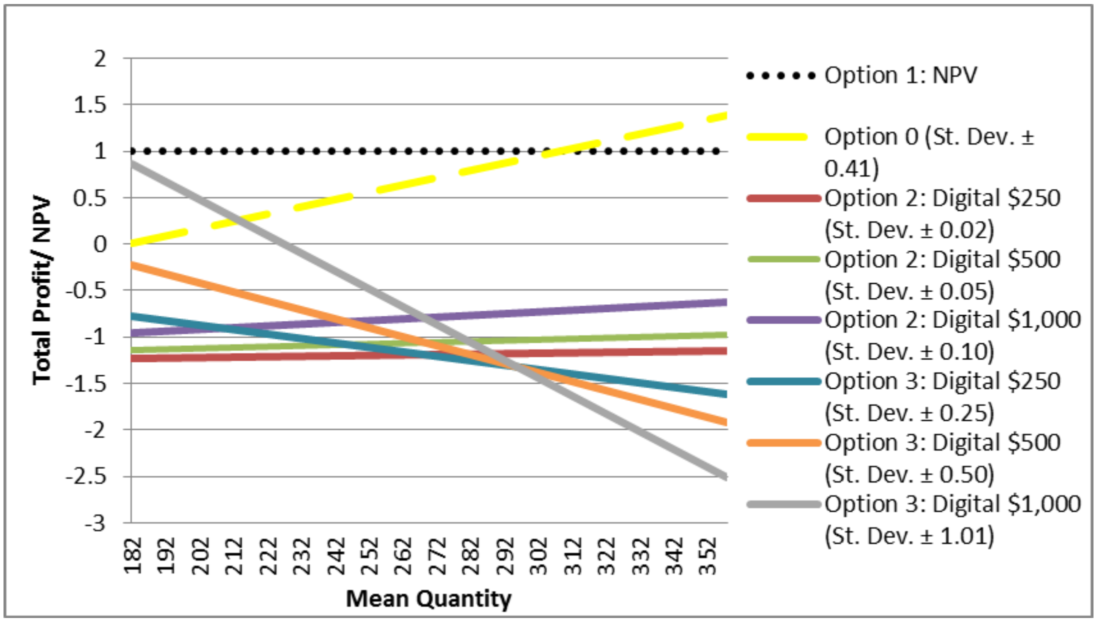


Figure 21 - Profit Margin Model, NRC $1,000,000- *Landing Gear*

When high non-recurring costs are present, industry should choose Option 1. Option 1 insures the industry can achieve a profit in 15 years. Option 2 and 3 cannot return the high initial investment within 15 years; industry would have to be confident government would be still requesting the files after 15 years to make a profit with Option 2 or 3.

When the non-recurring costs are low Option 2 is the stable business model protects industry from losing a profit. Option 2 always provides a higher profit than Option 0 and 1 when a low non-recurring cost exists. If industry identifies a lower demand is expected than what was forecasted, then industry should implement Option 3. Option 3 should never be implemented if there is a high variability in demand.

Additive Manufacturing

A profit margin model is executed again with data based on industry producing spare parts with AM. For Option 2 and 3 it should be noted the profits will remain the same as in the traditional manufacturing profit margin model, the changing cost is the non-recurring costs, and therefore the time to recoup non-recurring costs will be analyzed. The results are shown below starting with Option 1.

Option 1 profit values:

Non-Recurring Costs $10,000: NPV= $27,658

Non-Recurring Costs $100,000: NPV= $103,857

Non-Recurring Costs $1,000,000: NPV= $776,679

Table 23 - Forecasted demand vs actual demand (Option 0 Profit Margin Model Results- *Landing Gear AM*)

	Total Profit 15 Years		
Demand	Non-Recurring Cost $10,000	Non-Recurring Cost $100,000	Non-Recurring Cost $1,000,000
Fixed 270	$65,994	$200,994	$1,550,994
270 ± 44	$65,589	$199,923	$1,543,256
182 ± 44	$42,151	$137,817	$1,094,484
358 ± 44	$91,231	$267,864	$2,034,197
	Total Years to Recoup NRC		
Fixed 270	3	8	10
270 ± 44	3	9	11
182 ± 44	4	12	14
358 ± 44	2	6	8

Industry producing spare parts with additive manufacturing decreases the profit achieved for Option 0, because the cost to produce the parts with AM is approximately four times more than traditional manufacturing. Tooling cost for the traditional model is amortized within the first two years and tooling cost is also calculated into the profit margin which returns a greater profit.

Table 24 - Forecasted demand vs actual demand (Option 2 Profit Margin Model Results- *Landing Gear AM*)

	Total Profit 15 Years		
Demand	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	$101,250	$202,500	$405,000
270 ± 44	$100,750	$201,500	$403,000
182 ± 44	$71,750	$143,500	$287,000
358 ± 44	$132,475	$264,950	$529,900
	Total Years to Recoup NRC ($10,000)		
Fixed 270	2	1	1
270 ± 44	2	1	1
182 ± 44	3	2	1
358 ± 44	1	1	1
	Total Years to Recoup NRC ($100,000)		
Fixed 270	15	8	4
270 ± 44	15	9	4
182 ± 44	>15	11	5
358 ± 44	12	6	3
	Total Years to Recoup NRC ($1,000,000)		
Fixed 270	>15	>15	>15
270 ± 44	>15	>15	>15
182 ± 44	>15	>15	>15
358 ± 44	>15	>15	>15

Table 25 - Forecasted demand vs actual demand (Option 3 Profit Margin Model Results- *Landing Gear AM*)

	Total Profit 15 Years		
Demand	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 270	$101,250	$202,500	$405,000
270 ± 44	$106,250	$212,500	$425,000
182 ± 44	$396,250	$792,500	$1,585,000
358 ± 44	-$211,000	-$422,000	-$844,000
	Total Years to Recoup NRC ($10,000)		
Fixed 270	2	1	1
270 ± 44	1	1	1
182 ± 44	1	1	1
358 ± 44	>15	>15	>15
	Total Years to Recoup NRC ($100,000)		
Fixed 270	15	8	4
270 ± 44	8	5	2
182 ± 44	5	2	1
358 ± 44	>15	>15	>15
	Total Years to Recoup NRC ($1,000,000)		
Fixed 270	>15	>15	>15
270 ± 44	>15	>15	>15
182 ± 44	>15	>15	10
358 ± 44	>15	>15	>15

The total profits for Option 2 and 3 are equivalent to the traditional manufacturing model, the parameter changing in Option 2 and 3 is the non-recurring cost, which effects the years needed to recoup NRC.

In general, the total years needed to recoup the non-recurring costs are less when industry produces with AM, because the tooling cost is eliminated.

Profit Margin Needed for 2 Year ROI

Table 26 - Profit Margin for 2 Year ROI ($10,000) - Landing Gear AM

Demand	**Option 0**	**Option 2 $250/file**	**Option 2 $500/file**	**Option 2 $1,000/file**	**Option 3 $250/file**	**Option 3 $500/file**	**Option 3 $1,000/file**
270 fixed	11%	7%	4%	2%	7%	4%	2%
182 ± 44	14%	9%	5%	2%	-11%	-15%	-16%
270 ± 44	17%	11%	5%	3%	-23%	-26%	-28%
358 ± 44	9%	6%	3%	2%	28%	24%	22%

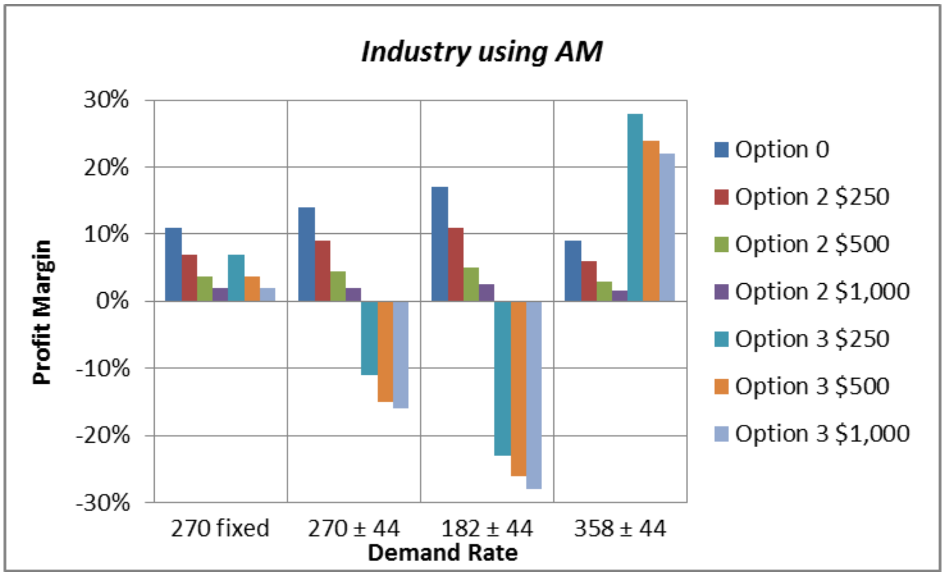


Figure 22 - Profit Margin for 2 Year ROI ($10,000) - *Landing Gear AM*

Table 27 - Profit Margin for 2 Year ROI ($100,000) - Landing Gear AM

Demand	Option 0	Option 2 $250/file	Option 2 $500/file	Option 2 $1,000/file	Option 3 $250/file	Option 3 $500/file	Option 3 $1,000/file
270 fixed	37%	74%	37%	19%	74%	37%	19%
182 ± 44	46%	91%	45%	23%	56%	19%	0%
270 ± 44	54%	110%	50%	26%	44%	7%	-11%
358 ± 44	31%	61%	31%	15%	95%	58%	39%

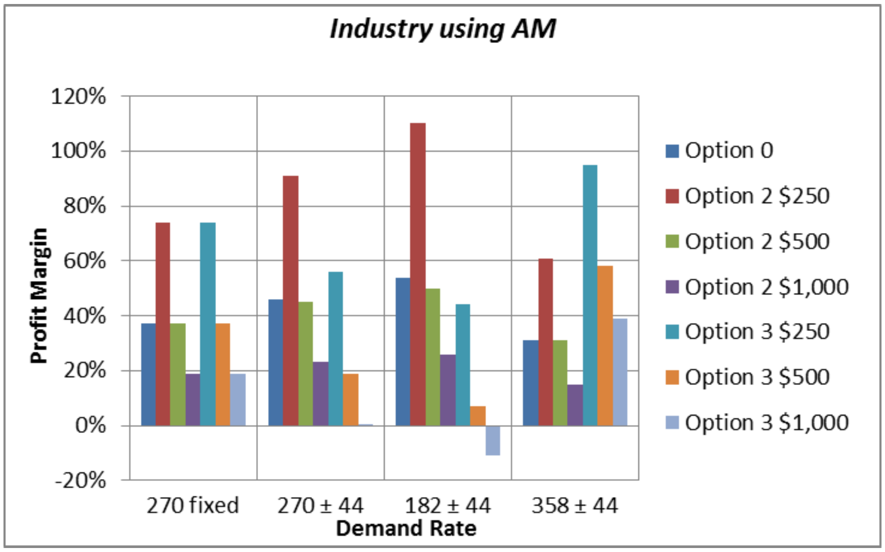


Figure 23 - Profit Margin for 2 Year ROI ($100,000) - *Landing Gear AM*

Table 28 - Profit Margin for 2 Year ROI ($1,000,000) - Landing Gear AM

Demand	Option 0	Option 2 $250/file	Option 2 $500/file	Option 2 $1,000/file	Option 3 $250/file	Option 3 $500/file	Option 3 $1,000/file
270 fixed	48%	740%	370%	190%	740%	370%	190%
182 ± 44	59%	910%	450%	230%	722%	352%	167%
270 ± 44	69%	1050%	500%	260%	711%	340%	155%
358 ± 44	40%	610%	310%	150%	761%	391%	206%

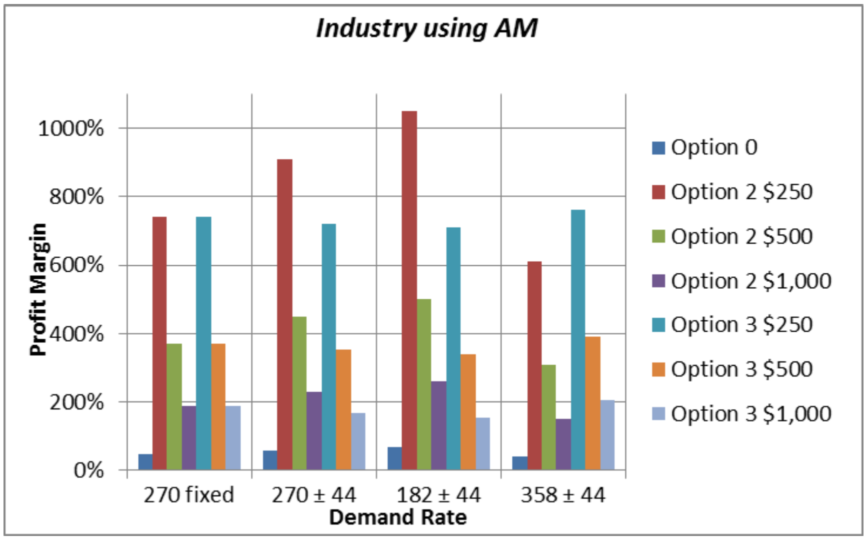


Figure 24 - Profit Margin for 2 Year ROI ($1,000,000) - *Landing Gear AM*

The profit margins are similar to the traditional model but slightly decreased.

Total Profit Ratio vs Mean Quantity Analysis

The total profit ratio vs mean quantity analysis was conducted for this model the results are similar to the previous profit margin model graphs, standard deviation for the AM profit margin are smaller. The total profit/NPV ratios are slightly lower for the AM profit margin model.

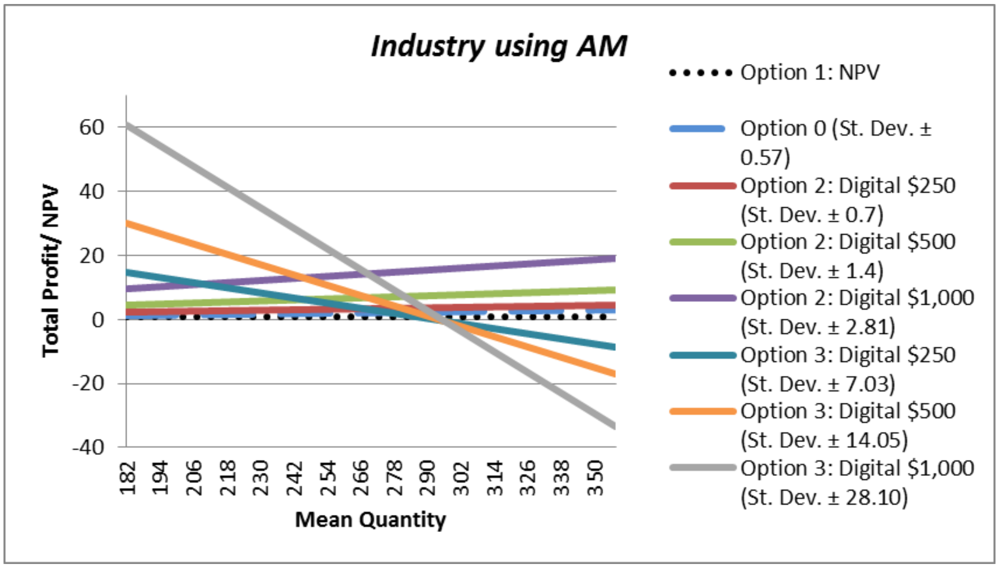


Figure 25 - Profit Margin Model, NRC $10,000- *Landing Gear*

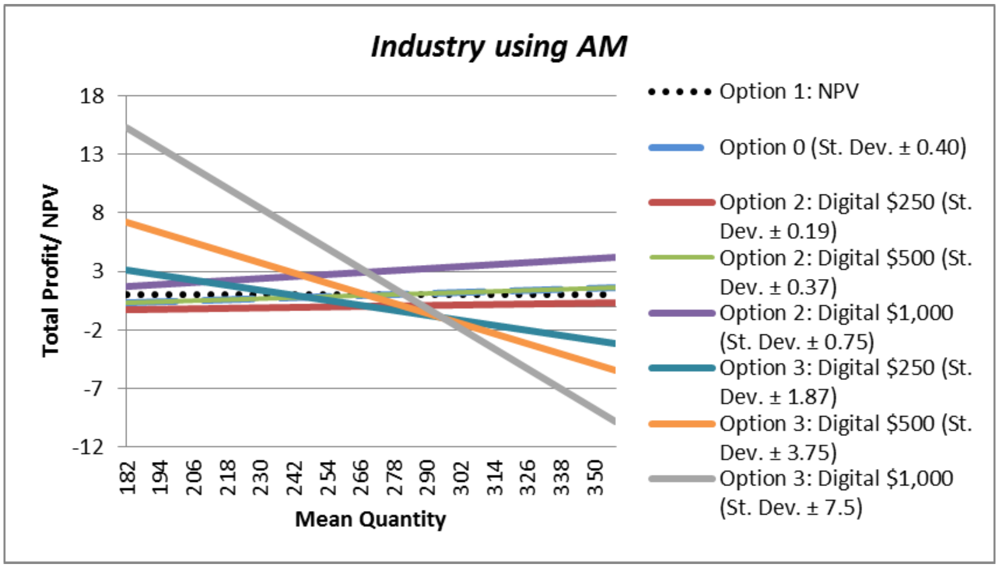


Figure 26 - Profit Margin Model, NRC $100,000- *Landing Gear*

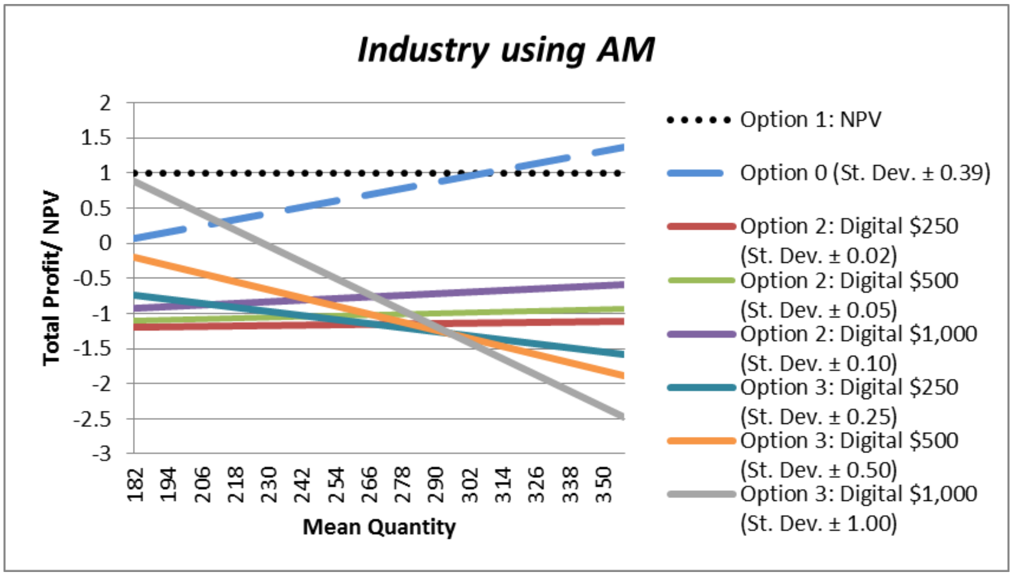


Figure 27 - Profit Margin Model, NRC $1,000,000- *Landing Gear*

4.2.2 Yoke Cover

4.2.2.1 Yoke Cover ROI Model Results

The yoke cover ROI model was calculated similarly to the landing gear ROI model. The difference are the values of the costs, and for the yoke cover case study, significant data existed which allowed for the calculation of a specific non-recurring cost, therefore non-recurring cost was not varied in the case study.

Option 1: NPV = $295,176

Table 29 - Forecasted demand vs actual demand (ROI Yoke Cover Results)

Total Profit 15 Years							
Demand	Option 0	Option 2			Option 3		
		Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 130	$675,000	$675,000	$675,000	$675,000	$675,000	$675,000	$675,000
130 ± 38	$663,305	$670,154	$670,154	$670,154	$678,500	$682,000	$689,000
92 ± 38	$358,514	$454,500	$454,500	$454,500	$834,250	$993,500	$1,312,000
168 ± 38	$999,406	$907,962	$907,962	$907,962	$506,750	$338,500	$2,000

Total Years to Recoup NRC ($90,000)							
Demand	Option 0	Option 2			Option 3		
		Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 130	2	2	2	2	2	2	2
130 ± 38	3	3	3	3	3	2	2
92 ± 38	3	3	3	3	2	2	2
168 ± 38	3	2	2	2	3	4	>15

Total Profit Ratio vs Mean Quantity Analysis

A total profit vs mean quantity analysis was conducted for the ROI yoke cover model. The graph confirms if a lower actual demand than forecasted exists, Option 3 achieves a greater profit. If a higher actual demand than forecasted exists, Option 2 achieves a greater profit. Option 2 is a stable business model that returns a profit higher than Option 1. Option 3 should not be implemented if the demand variations are high, industry can risk losing money.

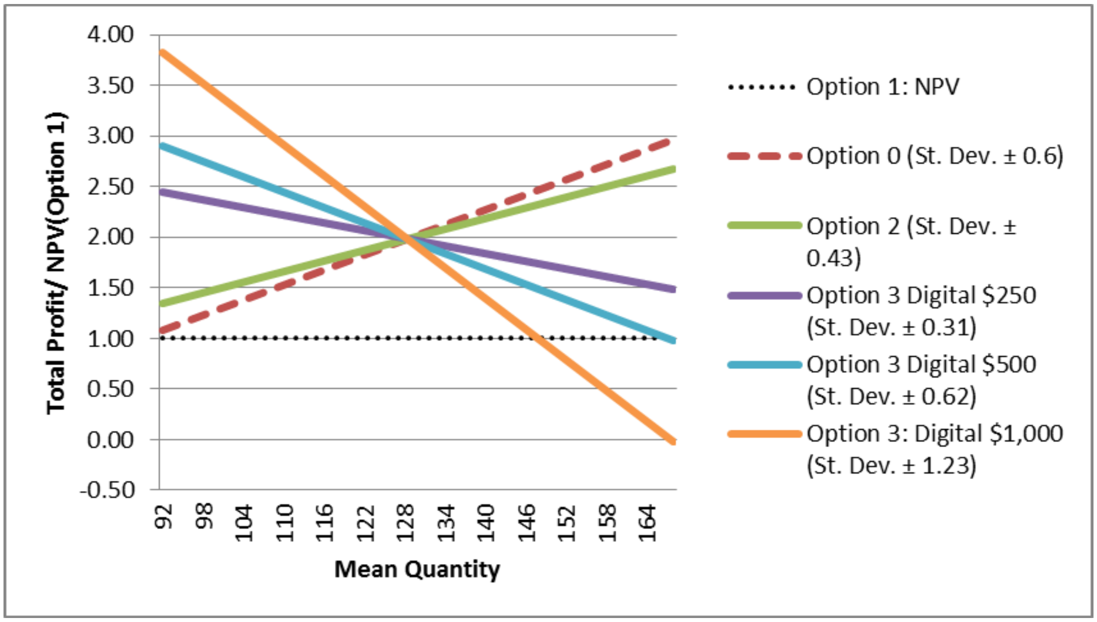


Figure 28 - ROI Model, Yoke Cover

4.2.2.2 Yoke Cover Profit Margin Model Results

Traditional Manufacturing

A profit margin model for the yoke cover was developed with a 10% profit margin.

Option 1: NPV = $89,131

Table 30 - Forecasted demand vs actual demand (Profit Margin Model Results-*Yoke Cover*)

Total Profit 15 Years							
Demand	Option 0	Option 2			Option 3		
		Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 130	$169,914	$48,750	$97,500	$195,000	$48,750	$97,500	$195,000
130 ± 38	$220,734	$48,400	$96,800	$193,600	$52,250	$104,500	$209,000
92 ± 38	$79,229	$32,825	$65,650	$131,300	$208,000	$416,000	$832,000
168 ± 38	$376,776	$65,575	$131,150	$262,300	-$119,500	-$239,000	-$478,000

Total Years to Recoup NRC ($90,000)							
Demand	Option 0	Option 2			Option 3		
		Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 130	3	>15	14	7	>15	14	7
130 ± 38	3	>15	15	8	>15	12	4
92 ± 38	8	>15	>15	10	9	5	1
168 ± 38	3	>15	11	6	>15	>15	>15

How industry should select the correct business model is similar to the landing gear profit model. All options experience the same type of results.

Profit Margin Needed for 2 Year ROI

The non-recurring cost for the yoke cover is $90,000 therefore in order to achieve a two year ROI; industry would have to sell an abundance of files over a longer period to achieve a profit able to cover the NRC and additional costs. From Figure 29 below the data shows a high range of profit margins for all options. For Option 2, a lower demand

and lower digital services costs both need a higher profit margin to obtain a two year ROI. Option 0 has the lowest profit margin because the tooling cost associated with injection molding is amortized in the first two years of the model.

Table 31 - Yoke Cover Profit Margin for 2 Year ROI ($90,000)

Demand	Option 0	Option 2 $250/file	Option 2 $500/file	Option 2 $1,000/file	Option 3 $250/file	Option 3 $500/file	Option 3 $1,000/file
130 Fixed	14%	138%	69%	35%	138%	69%	35%
130 ± 38	16%	148%	74%	37%	132%	63%	28%
92 ± 38	38%	250%	125%	63%	94%	25%	-10%
168 ± 38	10%	119%	60%	30%	154%	85%	50%

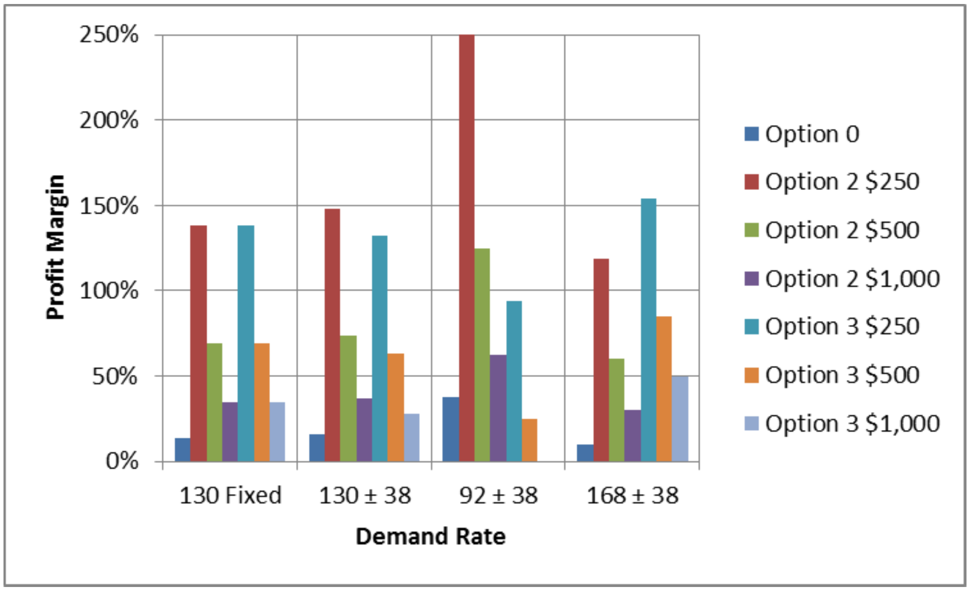


Figure 29 - Yoke Cover Profit Margin for 2 Year ROI ($90,000)

Total Profit Ratio vs Mean Quantity Analysis

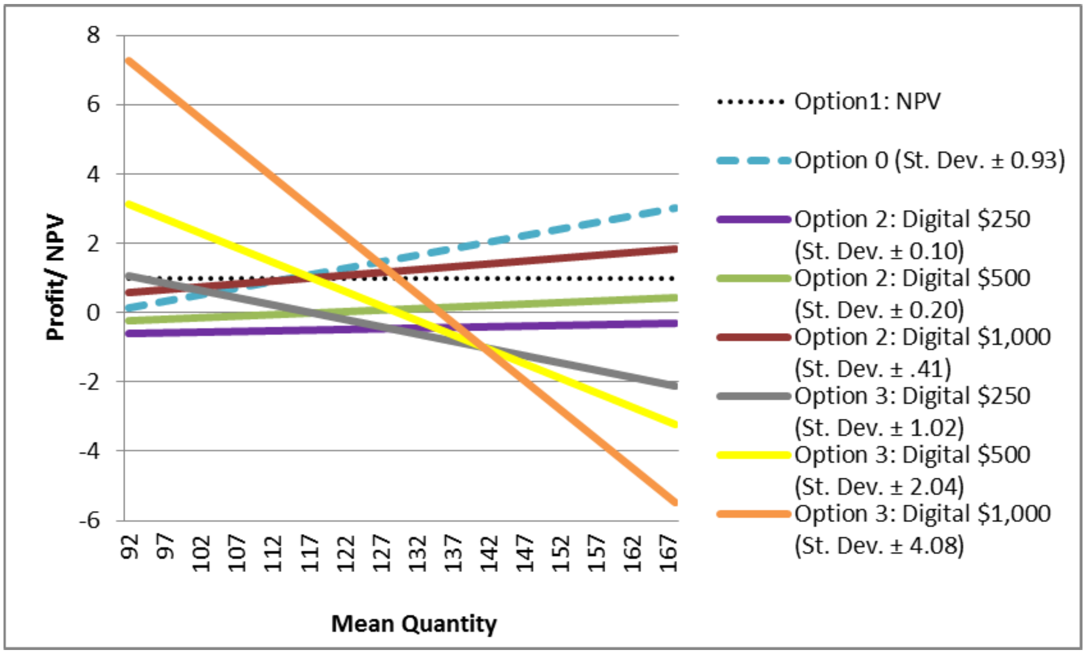


Figure 30 - Yoke Cover Profit Margin Model

The yoke cover results portray the effects each business model has on the total profit more accurately than the landing gear case study, because of the data obtained.

When the digital service cost is lower ($250 per file), Option 2 and 3 do not return a higher profit than Option 1. If industry wants to implement Option 2 or 3, a higher digital service cost is needed in order to return a greater profit than selling the TDP upfront for the price equivalent to the Net Present Value (Option 1).

When the digital service cost is higher ($1,000 per file), if a lower demand is expected Option 3 should be chosen to achieve a greater profit. If a higher demand is expected, Option 2 will achieve a greater profit because it is a cost per file model. Option 3 should not be implemented if a high demand variation is forecasted, industry will risk losing money. Overall to achieve a profit higher than Option 1, Option 2 should be implemented with a high digital services cost. Implementing a cost per file per use model allows the industry to insure a return on investment and maintain a profit equivalent to Option 0.

Additive Manufacturing

A second profit margin model is constructed for the scenario pertaining to industry producing the yoke covers spare parts with material extrusion instead of injection molding.

Option 1: NPV= $35,828

Table 32 - Forecasted demand vs actual demand (Profit Margin Model Results-*Yoke Cover AM*)

Total Profit 15 Years

Demand	Option 0	Option 2			Option 3		
		Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 130	$68,482	$48,750	$97,500	$195,000	$48,750	$97,500	$195,000
130 ± 38	$67,097	$48,400	$96,800	$193,600	$52,250	$104,500	$209,000
92 ± 38	$34,814	$32,825	$65,650	$131,300	$208,000	$416,000	$832,000
168 ± 38	$102,697	$65,575	$131,150	$262,300	-$119,500	-$239,000	-$478,000

Total Years to Recoup NRC ($30,000)

Demand	Option 0	Option 2			Option 3		
		Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file	Digital Services $250/file	Digital Services $500/file	Digital Services $1,000/file
Fixed 130	7	10	5	3	10	5	3
130 ± 38	7	9	5	3	6	5	2
92 ± 38	12	14	7	4	2	2	1
168 ± 38	5	8	4	2	>15	>15	>15

Profit Margin Needed for 2 Year ROI

Figure 31 reveals the cost savings associated with AM production. From a traditional to an additive production model it can be concluded lower profit margins are needed to recoup initial investments within two years. The reason is industry no longer has a $60,000 tooling cost as a non-recurring cost. A demand rate equal or greater than the forecasted demand results in a lower profit margin for Option 2. A higher digital service cost also insures industry will recoup the NRC. Option 3 achieves a high profit when the demand is lower than forecasted and a high profit margin is needed to achieve a two year ROI when the demand is higher than the forecasted quantity.

Table 33 - AM Yoke Cover Profit Margin for 2 Year ROI ($30,000)

Demand	Option 0	Option 2 $250/file	Option 2 $500/file	Option 2 $1,000/file	Option 3 $250/file	Option 3 $500/file	Option 3 $1,000/file
130 Fixed	33%	46%	23%	12%	46%	23%	12%
130 ± 38	36%	49%	24%	12%	40%	17%	5%
92 ± 38	64%	82%	42%	21%	2%	-22%	-33%
168 ± 38	28%	40%	20%	10%	62%	39%	27%

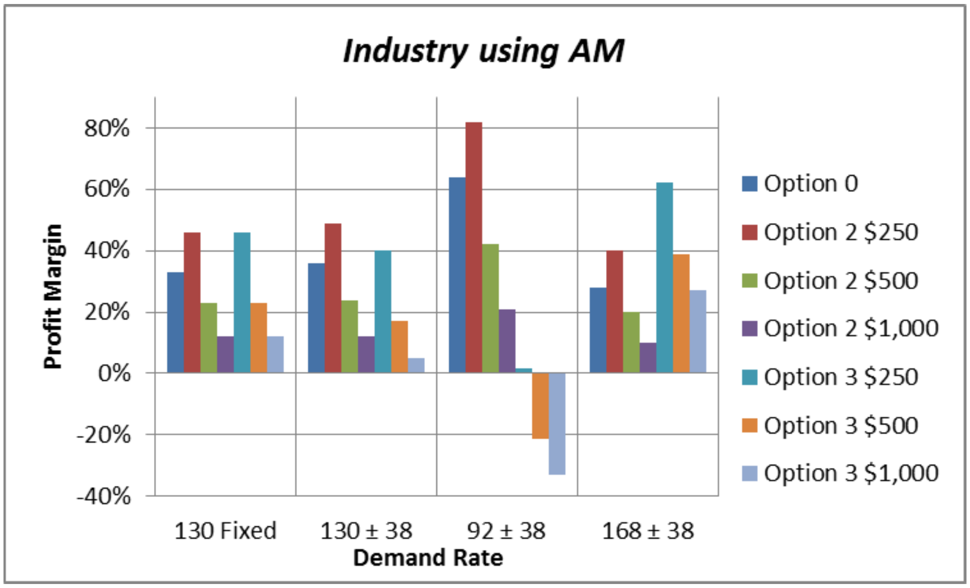


Figure 31 - AM Yoke Cover Profit Margin for 2 Year ROI ($30,000)

Total Profit Ratio vs Mean Quantity Analysis

When the scenario is switched to industry producing spare parts with AM, the total profit vs mean quantity graph displays a higher standard deviation for all options. Option 3 can achieve a 25 times greater profit than Option 1 if the demand variation is lower than the forecasted demand. Industry would be taking a risk if the demand was higher than the forecasted demand and it could result is profit loss. As the digital services cost decreases for Option 3, the standard deviation decreases and the profit also decreases, however when the demand is greater than forecasted, having a lower digital services cost has a lower profit loss outcome. Option 2 has lower standard deviations compared to Option 3. The impact of the digital services cost for Option 2 has an important effect of profit. From Figure 32 it is clear that an increase in digital services costs insures the industry a greater profit than Option 0 and 1 and a more stable outcome than Option 3.

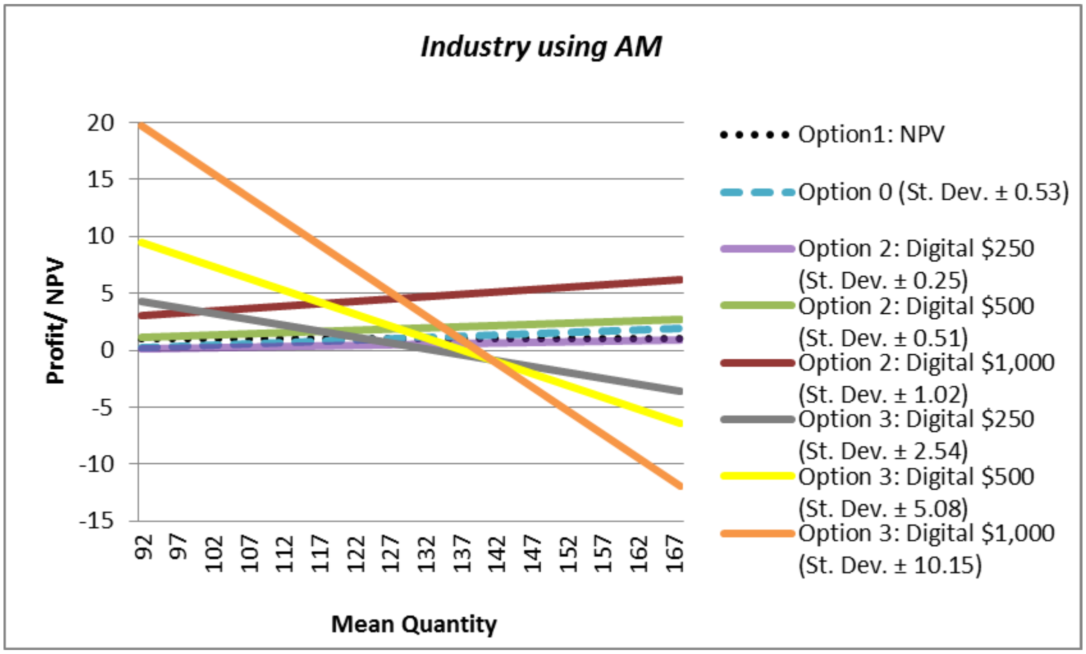


Figure 32 - Yoke Cover AM Profit Margin Model

4.3 Optimal Stocking Level

The costs and other values associated with both the traditional manufacturing process (CNC) and AM (EOS M290) are shown in table 19. Table 19 includes costs associated with different batch sizes, from the maximum parts that can be produced in one build, which is four parts, to the minimum of one part. For AM the holding cost, stock out penalty and cost per part decreases as the batch size increases. For the CNC costs, batch size does not affect the total cost [99].

Table 34 - Values used for optimal stocking level analysis

	CNC	***EOS (4 Parts)***	***EOS (3 Parts)***	***EOS (2 Parts)***	***EOS (1 Part)***
Cost / part	$1,358.25	$688.75	$875.09	$1,247.75	$2,365.75
Holding Cost / part (h)	$407.47	$206.62	$262.52	$374.32	$709.72
Lead time / year (τ)	0.0029389	0.0022542	0.0018161	0.0013769	0.0009377
Stock out penalty (γ)	$67.91	$34.44	$43.75	$62.39	$118.29

For the optimal stocking level analysis the demand rate was varied from 5-100. Low demands are ideal for aerospace spare part production. The stocking level, stock out probability and inventory costs were calculated. Tables 28 - 32 display the optimal stocking level that minimizes the inventory cost, along with the stock out probability associated with the demand, stocking level and specific part.

Table 35 - CNC Optimal Stocking Levels

	CNC		
Demand	S	p(s)	C(s)
5	0	1	$339.56
10	1	0.0004	$415.23
50	2	0.0093	$787.30
100	2	0.0322	$918.39

Table 36 - Optimal Stocking Levels for AM production with batch size 4

	EOS (4 Parts)		
Demand	s	p(s)	C(s)
5	0	1	$172.19
10	1	0.022	$209.66
50	1	0.101	$360.11
100	2	0.02	$437.57

Table 37 - Optimal Stocking Levels for AM production with batch size 3

	EOS (3 Parts)		
Demand	s	p(s)	C(s)
5	0	1	$218.77
10	1	0.0178	$265.65
50	1	0.0832	$422.79
100	2	0.0138	$538.26

Table 38 - Optimal Stocking Levels for AM production with batch size 2

	EOS (2 Parts)		
Demand	s	p(s)	C(s)
5	0	1	$311.94
10	1	0.0135	$377.72
50	1	0.0644	$551.14
100	2	0.0082	$749.09

Table 39 - Optimal Stocking Levels for AM production with batch size 1

	EOS (1 Part)		
Demand	s	p(s)	C(s)
5	0	1	$591.44
10	1	0.0092	$714.12
50	1	0.0448	$942.83
100	2	0.004	$1,400.52

The tables conclude maximizing the build volume for AM results in lower inventory cost for all demand rates 5-100. However, the stock out probability does increase as the batch size increases because of the longer lead time needed to produce a greater total of parts at once.

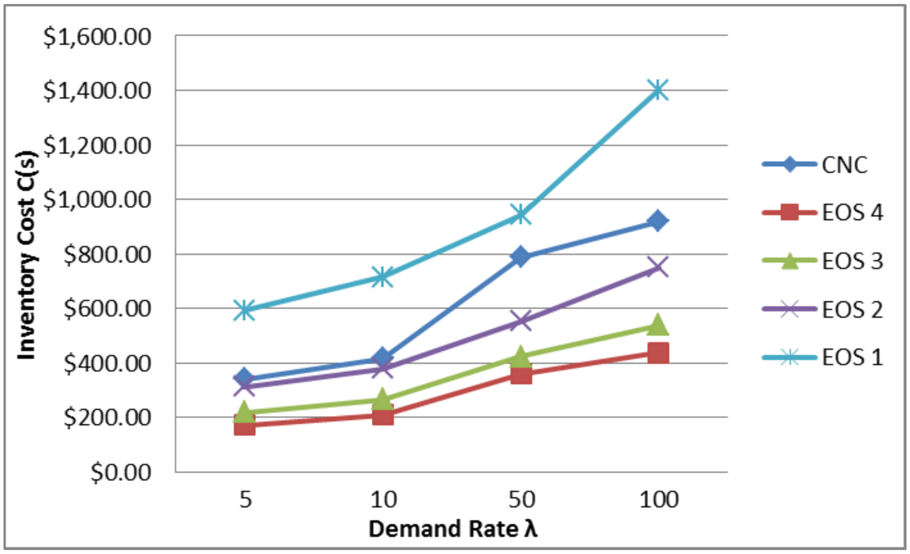


Figure 33 - Impact of demand on inventory costs.

Figure 33 displays how demand impacts the inventory cost. As the demand increases the cost of inventory also increases. The inventory cost is impacted by the stock out penalty and the stocking level. Traditional manufacturing (CNC) inventory costs are between producing the part with AM for a batch size of two and one. Therefore, AM should be implemented when the build volume of the machine can be maximized.

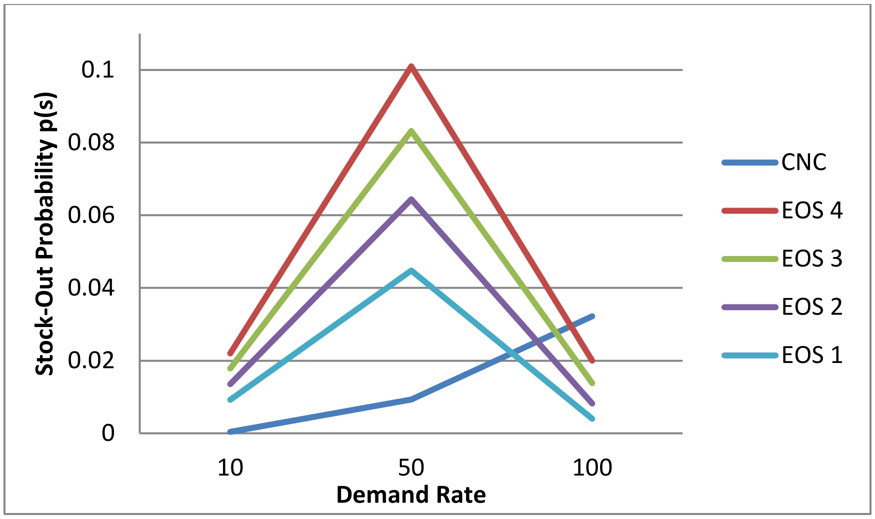


Figure 34 - The impact demand rate has on stock out probability

Figure 34 compares the stock out probability with the demand rate. Results for a demand rate of five are not shown because the probability of stock out for all processes is one. For AM, a peak is seen in Figure 34, which is a result of the stocking level changing when the demand increases from 50 to 100. For demand 10 and 50 the stocking level is calculated to be one part. Therefore as the demand increases from 10 to 50, the stock out probability also increases, as shown in Figure 34. However, when demand reaches 100, the optimal stocking level becomes two parts, therefore the stock out probability decreases because of the increase in inventory.

The advantage of using AM over traditional manufacturing is the ability to produce multiple parts in the same build therefore reducing the overall production cost and lead time per part. When the demand is low, stocking level can be reduced to one or even zero depending whether the part is mission critical. This allows for government to reduce costs and lead time of spare parts.

Chapter 5 Conclusion and Future Work

This research investigated four business models from industry's perspective in the scenario government would be producing spare parts in house. A survey was distributed to industry and government members and the responses were used to set a baseline for the business models. 60% of industry participants expected a return in investment in less than 2 years, but approximately 80% of government participants selected 4 or more years for a return in investment. The analysis was conducted from industry's perspective therefore a 2 year ROI was assumed. Government and industry participants agreed on government paying for certification and qualification costs which is also assumed in this study. In this research digital services cost was varied to account for the varied responses on what should be included in the services offered to government and the cost of the TDP. Both an ROI and profit margin model are used in this study but there is more emphasis on profit margin because the majority of industry responses for how industry obtains profit was through a profit margin.

Two case studies were applied to the business models, one on metal AM production and the other on plastic AM production, in order to determine how the different variables affected the business models.

Key findings:

A subscription based data business model (Option 3) provides better profit versus a per/part-file model (Option 2) if quantities are lower than expected.

A subscription based data business model (Option 3) is more profitable for the manufacturer for less than anticipated quantities of spare parts as long as the profit exceeds that of selling the data outright upfront (Option 1).

However, when the actual demand is higher than the original forecasted demand, a subscription based model can be a risk to industry. The more files requested from industry, the more expensive it is for the industry to maintain all of the files, if the cost to maintain the files exceeds the annual subscription fee then industry will begin to lose money.

If there is uncertainty in the quantities of spare part production requiring data files, a cost per file per use model (Option 2) should be implemented. When a high demand variation exists, Option 2 is a secure model that increases the likelihood of a profit greater than selling the data outright for the net present value (Option 1). The previous statement can be affected depending on the digital services cost associated with the TDP. Assuming that profit is based on a percentage of the cost of the data, a lower digital service cost can lead to a lower profit where a higher digital service cost guarantees a higher profit compared to Option 0 and 1.

The more expensive the initial investment industry makes for the spare part production also affects the profit that can be achieved. A larger NRC will take industry more than 15 years to pay off the costs. Implementing a higher profit margin can allow for a faster return on investment, this would determined by the company’s preference and what the government will accept during negotiations.

The variables affecting the NPV model (Option 1) are the non-recurring costs associated with producing the spare part, specifically if there are tooling costs. The yoke cover profit margin model comparing the traditional and additive methods to produce the spare part, the NPV is higher for the traditional method because the traditional method has higher non-recurring costs which lead to a larger profit per year and tooling amortized within the first two years of the net present value calculation.

Overall, a data driven spare parts model can be profitable for industry if properly incentivized and the correct data business model is selected.

Future Work

The business model study conducted is a beginning phase for implementing additive manufacturing into the DoD for maintenance and sustainment efforts. Additional variables will be added to the business models to account for all costs associated with an industry business model. A specific part will be selected from an industry member and research will be conducted by collaborating with industry and developing a cost model based on data given from industry. There is a need to develop the business models based on quantity affecting the selling price per part or per file. A business model from government's perspective also needs to be developed and compared to industry's goals.

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April 27, 2017

Dr. Brett Conner, Principal Investigator
Ms. Ashley Martof, Co-investigator
Department of Mechanical and Industrial Engineering
UNIVERSITY

RE: HSRC PROTOCOL NUMBER: 186-2017
PROTOCOL TITLE: Additive Manufacturing Business Model Survey

Dear Dr. Conner and Ms. Martof:

The Institutional Review Board has reviewed the abovementioned protocol and determined that it is exempt from full committee review based on a DHHS Category 3 exemption.

Any changes in your research activity should be promptly reported to the Institutional Review Board and may not be initiated without IRB approval except where necessary to eliminate hazard to human subjects. Any unanticipated problems involving risks to subjects should also be promptly reported to the IRB.

The IRB would like to extend its best wishes to you in the conduct of this study.

Sincerely,

Michael A. Hripko
Associate Vice President for Research
Authorized Institutional Official

MAH:cc

c: Dr. Hazel Marie, Chair
Department of Mechanical and Industrial Engineering